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Correlation between mechanical and ultrasonic responses for anisotropic behavior of soils

Jagannath, S. V., Ph.D.
The University of Arizona, 1991
CORRELATION BETWEEN MECHANICAL AND ULTRASONIC RESPONSES FOR ANISOTROPIC BEHAVIOR OF SOILS

by

S. V. JAGANNATH

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF CIVIL ENGINEERING AND ENGINEERING MECHANICS
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
WITH A MAJOR IN CIVIL ENGINEERING
In the Graduate College
THE UNIVERSITY OF ARIZONA

1991
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by S.V. Jagannath entitled:

Correlation Between Mechanical and Ultrasonic Responses for Anisotropic Behavior of Soils

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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SIGNED: S. V. Jagannath.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>VIII</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>XIV</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>XV</td>
</tr>
<tr>
<td>CHAPTER 1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Objective and Scope of Research</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Organization of Text</td>
<td>4</td>
</tr>
<tr>
<td>CHAPTER 2. REVIEW OF LITERATURE</td>
<td>5</td>
</tr>
<tr>
<td>2.1 General</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Review on Anisotropic Response of Geologic Materials</td>
<td>5</td>
</tr>
<tr>
<td>2.3 Review on Non Destructive Test Methods for Material Characterization</td>
<td>9</td>
</tr>
<tr>
<td>2.4 Review on Ultrasonic Testing</td>
<td>13</td>
</tr>
<tr>
<td>2.4.1 Basic principles of ultrasonic testing</td>
<td>13</td>
</tr>
<tr>
<td>2.4.2 Ultrasonic methods for material characterization</td>
<td>20</td>
</tr>
<tr>
<td>CHAPTER 3. DESCRIPTION OF RESEARCH</td>
<td>27</td>
</tr>
<tr>
<td>3.1 General</td>
<td>27</td>
</tr>
<tr>
<td>3.2 Mechanics of Proposed Method</td>
<td>28</td>
</tr>
<tr>
<td>3.3 Ultrasonic and Mechanical Testing</td>
<td>30</td>
</tr>
<tr>
<td>3.3.1 Ultrasonic device</td>
<td>30</td>
</tr>
<tr>
<td>3.3.2 Modification of the multi-axial device</td>
<td>32</td>
</tr>
<tr>
<td>3.3.3 Data acquisition system</td>
<td>33</td>
</tr>
<tr>
<td>3.4 Material and Sample Preparation</td>
<td>33</td>
</tr>
<tr>
<td>CHAPTER</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>CHAPTER 4. ULTRASONIC AND MECHANICAL TESTING PROGRAM</td>
<td>39</td>
</tr>
<tr>
<td>4.1 General</td>
<td>39</td>
</tr>
<tr>
<td>4.2 Testing Procedure</td>
<td>39</td>
</tr>
<tr>
<td>4.2.1 Types of tests</td>
<td>39</td>
</tr>
<tr>
<td>4.2.2 Calibration of the ultrasonic device</td>
<td>41</td>
</tr>
<tr>
<td>4.2.3 Calibration of the cubical device</td>
<td>41</td>
</tr>
<tr>
<td>4.2.4 Specimen installation and testing</td>
<td>41</td>
</tr>
<tr>
<td>4.3 Test Results</td>
<td>43</td>
</tr>
<tr>
<td>4.3.1 HC test</td>
<td>43</td>
</tr>
<tr>
<td>4.3.2 CTC20 test</td>
<td>50</td>
</tr>
<tr>
<td>4.3.3 CTC30 test</td>
<td>60</td>
</tr>
<tr>
<td>4.3.4 TE45 test</td>
<td>66</td>
</tr>
<tr>
<td>4.3.5 TC30 test</td>
<td>73</td>
</tr>
<tr>
<td>4.3.6 TE30 test</td>
<td>76</td>
</tr>
<tr>
<td>4.3.7 CTC10 test</td>
<td>87</td>
</tr>
<tr>
<td>4.4 Summary of Test Results</td>
<td>87</td>
</tr>
<tr>
<td>CHAPTER 5. DETERMINATION OF PARAMETERS AND VERIFICATION OF THE MODEL</td>
<td>95</td>
</tr>
<tr>
<td>5.1 General</td>
<td>95</td>
</tr>
<tr>
<td>5.2 Determination of Material Parameters for $\delta_1$ Model</td>
<td>95</td>
</tr>
<tr>
<td>5.2.1 Elastic constants, $E$, $\nu$</td>
<td>96</td>
</tr>
<tr>
<td>5.2.2 Ultimate parameters, $\gamma, \beta$ and $m$</td>
<td>98</td>
</tr>
<tr>
<td>5.2.3 The phase change parameter, $n$</td>
<td>98</td>
</tr>
<tr>
<td>5.2.4 Hardening parameters $a_1$ and $\eta_1$</td>
<td>98</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS ...(continued)

CHAPTER                                                                 page

5.2.5 Non-associative parameter, $\kappa$ ........................................... 100
5.3 Verification of the Model ................................................................. 100
5.3.1 Back prediction of test results ...................................................... 100

CHAPTER 6. MECHANICAL AND ULTRASONIC ANISOTROPY ............................ 106
6.1 General ................................................................................................. 106
6.2 Mechanical Anisotropy ......................................................................... 106
6.2.1 Determination of Mechanical Anisotropy, $M_{anis}$ ......................... 108
6.3 Ultrasonic Anisotropy ........................................................................... 112
6.4 Comparison of Mechanical and Ultrasonic Anisotropy ......................... 112
6.5 Correlation Functions ........................................................................... 124
6.5.1 Correlation functions for initial and induced anisotropy .................... 124
6.6 Potential Applications ........................................................................... 131

7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS .......................... 138
7.1 Summary and Conclusions .................................................................... 138
7.2 Recommendations for Future Work .................................................... 139

LIST OF REFERENCES ............................................................................... 140
LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Schematic of Proposed Study</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Schematic of the Yield Function in Various Spaces</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Schematic of Ultrasonic Testing</td>
<td>14</td>
</tr>
<tr>
<td>2.3a</td>
<td>Variation of P-wave Velocities in the Upper Mantle of the Pacific Ocean</td>
<td>25</td>
</tr>
<tr>
<td>2.3b</td>
<td>Variation of P-wave Velocities near Hawaii</td>
<td>25</td>
</tr>
<tr>
<td>2.4</td>
<td>Field Observations of Ultrasonic Velocities adjacent to a Tunnel</td>
<td>26</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic of Multi-axial Ultrasonic Testing</td>
<td>29</td>
</tr>
<tr>
<td>3.2</td>
<td>Setup for Ultrasonic and Mechanical Testing</td>
<td>31</td>
</tr>
<tr>
<td>3.3</td>
<td>Exploded view of the Cubical Device and Details of Mounting</td>
<td>34</td>
</tr>
<tr>
<td>3.4</td>
<td>Details of VT-101 Transducer Mounting</td>
<td>35</td>
</tr>
<tr>
<td>3.5</td>
<td>Assembled View of VT-101 Transducer</td>
<td>35</td>
</tr>
<tr>
<td>3.6</td>
<td>Accessories for Sample Preparation</td>
<td>37</td>
</tr>
<tr>
<td>3.7</td>
<td>Cured Cemented Sand Sample</td>
<td>38</td>
</tr>
<tr>
<td>4.1</td>
<td>Proposed Laboratory Stress Paths</td>
<td>40</td>
</tr>
<tr>
<td>4.2</td>
<td>Calibration of the Ultrasonic Unit</td>
<td>42</td>
</tr>
<tr>
<td>4.3</td>
<td>Flow Chart of the Testing Procedure</td>
<td>44</td>
</tr>
<tr>
<td>4.4</td>
<td>Stress-Strain Plot for HC test</td>
<td>45</td>
</tr>
<tr>
<td>4.5</td>
<td>Stress-Velocity Plot for HC Test</td>
<td>46</td>
</tr>
<tr>
<td>4.6</td>
<td>Stress-Attenuation for HC Test</td>
<td>46</td>
</tr>
<tr>
<td>4.7</td>
<td>Wave Signatures along X,Y and Z directions for HC Test at</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Confining Pressures of (a) 0 psi (b) 30 psi (207 kPa)</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>4.8</td>
<td>Wave Signatures along X,Y and Z directions for HC Test at Confining Pressures of (a) 60 psi (414 kPa) (b) 90 psi (620 kPa)</td>
<td>49</td>
</tr>
<tr>
<td>4.9</td>
<td>Stress-Strain Response for CTC20 test $\sigma_0 = 20$ psi (138 kPa)</td>
<td>51</td>
</tr>
<tr>
<td>4.10</td>
<td>Volumetric Response for CTC20 Test $\sigma_0 = 20$ psi (138 kPa)</td>
<td>51</td>
</tr>
<tr>
<td>4.11</td>
<td>Stress-Velocity Plot during HC part of CTC20 Test</td>
<td>52</td>
</tr>
<tr>
<td>4.12</td>
<td>Stress-Attenuation Plot during HC part of CTC20 Test</td>
<td>52</td>
</tr>
<tr>
<td>4.13</td>
<td>Wave Signatures along X,Y and Z directions for CTC20 Test for at $\tau_{oct}$ of (a) 0 psi (b) 9.43 psi (65 kPa)</td>
<td>53</td>
</tr>
<tr>
<td>4.14</td>
<td>Wave Signatures along X,Y,Z directions for CTC20 test at $\tau_{act}$ of (a) 0 psi (after first unloading) (b) 12.3 psi (84.4 kPa)</td>
<td>55</td>
</tr>
<tr>
<td>4.15</td>
<td>Wave Signatures along X,Y,Z directions for CTC20 Test at $\tau_{act}$ of (a) 18.9 psi (130 kPa) (b) 0 psi (after second unloading cycle)</td>
<td>56</td>
</tr>
<tr>
<td>4.16</td>
<td>Wave Signatures along X,Y,Z directions for CTC20 Test at $\tau_{act}$ of (a) 20.3 psi (140 kPa) (b) 22.9 psi (158 kPa)</td>
<td>57</td>
</tr>
<tr>
<td>4.17</td>
<td>Variation of Velocity with $\tau_{oct}$ for CTC20 test</td>
<td>58</td>
</tr>
<tr>
<td>4.18</td>
<td>Variation of Attenuation with $\tau_{oct}$ for CTC20 test</td>
<td>59</td>
</tr>
<tr>
<td>4.19</td>
<td>Stress-Strain Response for CTC30 test with $\sigma_0 = 30$ psi (207 kPa)</td>
<td>61</td>
</tr>
<tr>
<td>4.20</td>
<td>Volumetric Response for CTC30 test with $\sigma_0 = 30$ psi (207 kPa)</td>
<td>61</td>
</tr>
<tr>
<td>4.21</td>
<td>Stress-Velocity Plot during HC part of CTC30 Test</td>
<td>62</td>
</tr>
<tr>
<td>4.22</td>
<td>Stress-Attenuation Plot during HC part of CTC30 Test</td>
<td>62</td>
</tr>
<tr>
<td>4.23</td>
<td>Wave Signatures along X,Y and Z directions for CTC30 test at $\tau_{oct}$ of (a) 0 psi (b) 5.6 psi (38.6 kPa)</td>
<td>63</td>
</tr>
<tr>
<td>4.24</td>
<td>Wave Signatures along X,Y and Z directions for CTC30 Test at $\tau_{act}$ of (a) 9.9 psi (68.2 kPa) (b) 0 psi (after first unloading)</td>
<td>64</td>
</tr>
<tr>
<td>4.25</td>
<td>Wave Signatures along X,Y and Z directions for CTC30 Test at $\tau_{act}$ of (a) 19.8 psi (136.4 kPa) (b) 22.5 psi (155 kPa)</td>
<td>65</td>
</tr>
<tr>
<td>4.26</td>
<td>Variation of Velocity with $\tau_{oct}$ for CTC30 Test</td>
<td>67</td>
</tr>
</tbody>
</table>
**LIST OF ILLUSTRATIONS (continued)**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.27</td>
<td>Variation of Attenuation with $\tau_{oct}$ for CTC30 test</td>
<td>68</td>
</tr>
<tr>
<td>4.28</td>
<td>Stress-Strain Response for TE45 test with $\sigma_0 = 45$ psi (310 kPa)</td>
<td>69</td>
</tr>
<tr>
<td>4.29</td>
<td>Volumetric Response for TE45 test with $\sigma_0 = 45$ psi (310 kPa)</td>
<td>69</td>
</tr>
<tr>
<td>4.30</td>
<td>Stress-Velocity Plot during HC part of TE45 test</td>
<td>70</td>
</tr>
<tr>
<td>4.31</td>
<td>Stress-Attenuation Plot during HC part of TE45 test</td>
<td>70</td>
</tr>
<tr>
<td>4.32</td>
<td>Wave Signatures along X,Y and Z directions for TE45 Test at $\tau_{oct}$ of (a) 0 psi (b) 4.24 psi (29.2 kPa)</td>
<td>71</td>
</tr>
<tr>
<td>4.33</td>
<td>Wave Signatures along X,Y and Z directions for TE45 Test at $\tau_{oct}$ of (a) 14.1 psi (97.2 kPa) (b) 19 psi (131 kPa)</td>
<td>72</td>
</tr>
<tr>
<td>4.34</td>
<td>Variation of Velocity with $\tau_{oct}$ for TE45 test</td>
<td>74</td>
</tr>
<tr>
<td>4.35</td>
<td>Variation of Attenuation with $\tau_{oct}$ for TE45 test</td>
<td>74</td>
</tr>
<tr>
<td>4.36</td>
<td>Stress-Strain Response for TC30 test with $\sigma_0 = 30$ psi (206.7 kPa)</td>
<td>75</td>
</tr>
<tr>
<td>4.37</td>
<td>Volumetric Response for TC30 test with $\sigma_0 = 30$ psi (206.7 kPa)</td>
<td>75</td>
</tr>
<tr>
<td>4.38</td>
<td>Stress-Velocity Plot during HC part of TC30 test</td>
<td>77</td>
</tr>
<tr>
<td>4.39</td>
<td>Stress-Attenuation Plot during HC part of TC30 test</td>
<td>77</td>
</tr>
<tr>
<td>4.40</td>
<td>Wave Signatures along X,Y and Z directions for TC30 Test at $\tau_{oct}$ of (a) 0 psi (b) 3 psi (20.4 kPa)</td>
<td>78</td>
</tr>
<tr>
<td>4.41</td>
<td>Wave Signatures along X,Y and Z directions for TC30 Test at $\tau_{oct}$ of (a) 0 psi (after first unloading) (b) 6 psi (42 kPa)</td>
<td>79</td>
</tr>
<tr>
<td>4.42</td>
<td>Wave Signatures along X,Y and Z directions for TC30 Test at $\tau_{oct}$ of (a) 10 psi (69 kPa) (b) 13 psi (90 kPa)</td>
<td>80</td>
</tr>
<tr>
<td>4.43</td>
<td>Variation of Velocity with $\tau_{oct}$ for TC30 test</td>
<td>81</td>
</tr>
<tr>
<td>4.44</td>
<td>Variation of Attenuation with $\tau_{oct}$ for TC30 test</td>
<td>81</td>
</tr>
<tr>
<td>4.45</td>
<td>Stress-Strain Response for TE30 test with $\sigma_0 = 30$ psi (207 kPa)</td>
<td>82</td>
</tr>
<tr>
<td>4.46</td>
<td>Volumetric Response for TE30 test with $\sigma_0 = 30$ psi (207 kPa)</td>
<td>82</td>
</tr>
<tr>
<td>4.47</td>
<td>Stress-Velocity Plot during HC part of TE30 test</td>
<td>83</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS ..... (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.48</td>
<td>Stress-Attenuation Plot during HC part of TE30 test</td>
<td>83</td>
</tr>
<tr>
<td>4.49</td>
<td>Wave Signatures along X,Y and Z directions for TE30 Test at $\tau_{oct}$ of (a) 0 psi (b) 3 psi (21 kPa)</td>
<td>84</td>
</tr>
<tr>
<td>4.50</td>
<td>Wave Signatures along X,Y and Z directions for TE30 Test at $\tau_{oct}$ of (a) 6 psi (42 kPa) (b) 10 psi (69 kPa)</td>
<td>85</td>
</tr>
<tr>
<td>4.51</td>
<td>Variation of Velocity with $\tau_{oct}$ for TE30 test</td>
<td>86</td>
</tr>
<tr>
<td>4.52</td>
<td>Variation of Attenuation with $\tau_{oct}$ for TE30 test</td>
<td>86</td>
</tr>
<tr>
<td>4.53</td>
<td>Stress-Strain Response for CTC10 test with $\sigma_0 = 10$ psi (69 kPa)</td>
<td>88</td>
</tr>
<tr>
<td>4.54</td>
<td>Volumetric Response for CTC10 test with $\sigma_0 = 10$ psi (69 kPa)</td>
<td>88</td>
</tr>
<tr>
<td>4.55</td>
<td>Wave Signatures along X,Y and Z directions for CTC10 Test at $\tau_{oct}$ of (a) 0 psi (b) 4.9 psi (34 kPa)</td>
<td>89</td>
</tr>
<tr>
<td>4.56</td>
<td>Wave Signatures along X,Y and Z directions for CTC10 Test at $\tau_{oct}$ of (a) 0 psi (after first unloading cycle) (b) 9.8 psi (68 kPa)</td>
<td>90</td>
</tr>
<tr>
<td>4.57</td>
<td>Wave Signatures along X,Y and Z directions for CTC10 Test at $\tau_{oct}$ of (a) 0 psi (after second unloading cycle) (b) 16.3 psi (112 kPa)</td>
<td>91</td>
</tr>
<tr>
<td>4.58</td>
<td>Variation of Velocity with $\tau_{oct}$ for CTC10 test</td>
<td>92</td>
</tr>
<tr>
<td>4.59</td>
<td>Variation of Attenuation with $\tau_{oct}$ for CTC10 test</td>
<td>93</td>
</tr>
<tr>
<td>5.1</td>
<td>Determination of Ultimate Parameter</td>
<td>99</td>
</tr>
<tr>
<td>5.2</td>
<td>Determination of Hardening Parameter</td>
<td>101</td>
</tr>
<tr>
<td>5.3</td>
<td>Back Prediction of CTC20 Test using $\delta_1$ Model</td>
<td>103</td>
</tr>
<tr>
<td>5.4</td>
<td>Back Prediction of CTC20 Test</td>
<td>103</td>
</tr>
<tr>
<td>5.5</td>
<td>Back Prediction of CTC30 Test</td>
<td>104</td>
</tr>
<tr>
<td>5.6</td>
<td>Back Prediction of CTC30 Test</td>
<td>104</td>
</tr>
<tr>
<td>5.7</td>
<td>Back Prediction of TE45 Test</td>
<td>105</td>
</tr>
<tr>
<td>5.8</td>
<td>Back Prediction of TE45 Test</td>
<td>105</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Definition of Mechanical Anisotropy</td>
<td>107</td>
</tr>
<tr>
<td>6.2</td>
<td>Variation of Mechanical Anisotropy for CTC20 Test</td>
<td>109</td>
</tr>
<tr>
<td>6.3</td>
<td>Variation of Mechanical Anisotropy for CTC30 Test</td>
<td>110</td>
</tr>
<tr>
<td>6.4</td>
<td>Variation of Mechanical Anisotropy for HC Tests</td>
<td>113</td>
</tr>
<tr>
<td>6.5</td>
<td>Variation of Velocity Anisotropy for HC Tests</td>
<td>115</td>
</tr>
<tr>
<td>6.6</td>
<td>Variation of Attenuation Anisotropy for HC Tests</td>
<td>116</td>
</tr>
<tr>
<td>6.7</td>
<td>Variation of Ultrasonic Anisotropy during loading and unloading for HC Tests</td>
<td>117</td>
</tr>
<tr>
<td>6.8</td>
<td>Variation of Mechanical and Ultrasonic Anisotropy for CTC20 Test</td>
<td>118</td>
</tr>
<tr>
<td>6.9</td>
<td>Decomposition of $M_{anis}$ to Hydrostatic and Shear Components for CTC20 Test</td>
<td>120</td>
</tr>
<tr>
<td>6.10</td>
<td>Variation of Mechanical and Ultrasonic Anisotropy for CTC30 Test</td>
<td>121</td>
</tr>
<tr>
<td>6.11</td>
<td>Decomposition of $M_{anis}$ to Hydrostatic and Shear Components for CTC30 Test</td>
<td>122</td>
</tr>
<tr>
<td>6.12</td>
<td>Variation of Mechanical and Ultrasonic Anisotropy for TE45 Test</td>
<td>123</td>
</tr>
<tr>
<td>6.13</td>
<td>Variation of Mechanical and Ultrasonic Anisotropy for TC30 Test</td>
<td>125</td>
</tr>
<tr>
<td>6.14</td>
<td>Variation of Mechanical and Ultrasonic Anisotropy for RTE30 Test</td>
<td>126</td>
</tr>
<tr>
<td>6.15</td>
<td>Comparison of predicted $M_{anis}$ using $V_{anis}$ and Experimental $M_{anis}$ for CTC30 Test</td>
<td>128</td>
</tr>
<tr>
<td>6.16</td>
<td>Comparison of predicted $M_{anis}$ using $A_{anis}$ and Experimental $M_{anis}$ for CTC30 Test</td>
<td>129</td>
</tr>
<tr>
<td>6.17</td>
<td>Comparison of predicted $M_{anis}$ using both $V_{anis}$ and $A_{anis}$ and Experimental $M_{anis}$ for CTC30 Test</td>
<td>130</td>
</tr>
<tr>
<td>6.18</td>
<td>Comparison of predicted $M_{anis}$ and Model $M_{anis}$ for CTC30 Test</td>
<td>132</td>
</tr>
<tr>
<td>6.19</td>
<td>Comparison of predicted $M_{anis}$ and Model $M_{anis}$ for TE45 Test</td>
<td>133</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6.20</td>
<td>Comparison of predicted $M_{anis}$ and Model $M_{anis}$ for TC30 Test</td>
<td>134</td>
</tr>
<tr>
<td>6.21</td>
<td>Comparison of predicted $M_{anis}$ and Model $M_{anis}$ for CTC20 Test</td>
<td>135</td>
</tr>
<tr>
<td>6.22</td>
<td>Prediction of in-situ Mechanical Anisotropy</td>
<td>136</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Relation Between Elastic Constants and Ultrasonic Velocity</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Ultrasonic Test Results for Rock Salt Specimens</td>
<td>23</td>
</tr>
<tr>
<td>2.3</td>
<td>Elastic Constants Based on Ultrasonic Velocity</td>
<td>97</td>
</tr>
</tbody>
</table>
ABSTRACT

A geologic material when subject to a sequence of loading, unloading and re-loading, exhibits anisotropic response. This is usually attributed to reorientation of particles and to the formation of micro-cracks and damage within the material and some of the constitutive models such as Hierarchical Single Surface (HISS) models can account for these effects. However to better understand and quantify induced anisotropy, alternate testing procedures such as Non Destructive Tests (NDT) are desirable.

An attempt has been made to develop a NDT procedure for the characterization of induced anisotropy in geologic materials and to compare, to quantify and to correlate such response with the anisotropic response as predicted by the constitutive model. Herein, the ultrasonic NDT method is used as a tool to quantify the anisotropic response of the material and the $\delta_1$ model of the HISS series of models is used to describe the mechanical anisotropy.

A unique and novel testing procedure which includes three-dimensional mechanical (destructive) testing combined with ultrasonic testing of cubical (cemented sand) samples under various stress paths has been developed. This involved the modification of existing stress-controlled truly triaxial device to incorporate ultrasonic testing and use of a state-of-the-art data acquisition system to acquire the data during the test. Mechanical response is presented in the form of stress-strain and volumetric responses, while, the ultrasonic response is presented in the form of wave signatures, velocities and attenuations. Also, special tests have been performed to observe the anisotropic response of a material in shear stress paths.

The quantification of mechanical anisotropy is made by using the $\delta_1$ model, while, the ultrasonic velocity and attenuations are used to define the ultrasonic anisotropies. The parameters which define the $\delta_1$ model are determined based on the test results, and the suitability of the model is verified by back-predicting the tests. Correlation functions which relates the mechanical anisotropy with the velocity anisotropy and the attenuation anisotropy have been developed. The potential applications of such functions are also discussed.
CHAPTER 1

INTRODUCTION

Realization that appropriate definition of constitutive behavior of (geologic) materials is required for realistic solutions of geomechanics problems, has spurred a significant activity toward both mathematical modelling and laboratory testing. Such efforts in the department of Civil Engineering and Engineering Mechanics at the University of Arizona, under the direction of Desai have helped to develop and to experimentally verify unified and hierarchical models for geologic materials.

Alternative to the above is field testing of geologic materials, a procedure in which the undisturbed material is tested in situ and the material constants which define the response behavior can be found. This approach is limited because loading and geometries are significantly restricted. A third option is the "Non Destructive Testing (NDT)" of geologic materials, the procedure in which the material response is obtained in the field or laboratory without destroying its physical state.

An important question that requires further study is how the mechanical response as measured through displacements and stresses can be related to the response measured by NDT. In other words, can the constitutive constants (or at least some of them) defined through the mechanical response be related to indirectly measured NDT parameters? If so can we obtain the correlation functions between them, which could then be used to define the material behavior? The primary objective of the present study is to find an answer to above questions.

The philosophy of the Hierarchical Single Surface (HISS) model developed by Desai and co-workers is that, one can select a model from the hierarchy of models, depending on the complexity of the material. The HISS plasticity based model in its simplest form can simulate isotropically hardening material with associative characteristics, and in its increasing complex forms can account for anisotropic hardening response, micro-cracks and damage. The anisotropic response of initially
anisotropic material is not well understood. In particular, the phenomenon of stress induced anisotropy, its quantification and its correlation with other physical measures is difficult to comprehend. Towards such an endeavor, this study has been performed.

1.1 Objective and Scope of Research

The main objectives of this research are (Figure (1.1)):

1. to investigate the feasibility of ultrasonic testing, as one of the NDT methods, for the characterization of geologic materials and to identify the measurable parameters to quantify anisotropy based on the principle of mechanics and ultrasonic testing.

2. to develop a novel testing procedure for combining ultrasonic and mechanical testing. This involves, modification of the existing stress-controlled cubical triaxial device (Sture and Desai, 1979; Desai, Phan and Sture, 1981), for ultrasonic measurements.

3. to determine the material parameters associated with the model, after performing a series of laboratory mechanical and ultrasonic tests on a cemented material under different stress paths of loading, unloading and re-loading. Also, to verify the suitability of the model by back-predicting the test results, and

4. to define and to quantify the mechanical anisotropy (based on the stress-strain response) and ultrasonic anisotropy (a physical measure), and to establish correlation functions between them.

In the context of the above objectives, various special and new contributions of this research can be stated as follows:

(a) a unique testing program which includes three-dimensional testing of cubical samples under various stress paths combined with ultrasonic testing, is first of its kind.

(b) analysis of wave propagation data at various stress states that provide insight into some of the important phenomena like initial and induced anisotropy.
Figure 1.1 Schematic of Proposed Study
(c) development of correlation functions would allow a new way of predicting and quantifying induced anisotropy, and
(d) possible extension of the proposed method for quantifying the anisotropy due to sample disturbance in the laboratory or in the field.

1.2 Organization of Text

Chapter 2 presents a review of literature on some of the existing NDT methods with a special emphasis on the ultrasonic method, followed by a review on modelling for anisotropic response. Emphasis is given to the recent developments in constitutive laws dealing with stress-induced anisotropy. Also a brief review on the factors which influence the ultrasonic testing of geologic (highly attenuating) materials is given.

Chapter 3 deals with the mechanics of the proposed research and details of experimental setup. The chapter also deals with the preparation of cemented sand samples for ultrasonic and mechanical testing.

In Chapter 4, the testing procedure is presented. Test results under various stress paths of loading, unloading and reloading are given. Also, test results for some special tests, which enable definitions of the mechanical and ultrasonic anisotropy are presented.

Chapter 5 is devoted to the determination of constitutive constants along with the verification of the model, by back prediction of test results. Chapter 6 also deals with the quantification of mechanical and ultrasonic anisotropy and the development of correlation functions between them. Also, potential applications of such correlation function are presented.

Finally, in Chapter 7, summary and conclusions of this research are presented, along with the recommendation for future work.
CHAPTER 2

REVIEW OF LITERATURE

2.1 General

A homogeneous material whose properties vary with direction is termed as anisotropic. Quantification of anisotropic behavior of such a material can be done by considering either the mechanical measure (based on laboratory/field destructive tests), as defined by a constitutive law or by a physical measure (based on non-destructive tests). In the light of the research presented herein, a brief review of literature pertaining to the anisotropic response of geologic materials and to the ultrasonic (non-destructive) testing of geologic materials has been presented. The content of this chapter is divided into three sections. The first section presents a review of the literature relevant to the anisotropic response of geologic materials and a brief description of HISS (Desai et al. 1986) model. In the second section, a review of NDT methods used in laboratory and field for material characterization is presented. The last section deals with the review of the ultrasonic method, which is used in the present study.

2.2 Review on Anisotropic Response of Geologic Materials

When soils are subjected to a loading sequence, there are considerable changes induced in the fabric or structure of the material. Such changes can cause an initially isotropic material to exhibit anisotropic characteristics. The degree of anisotropy so induced, continuously evolves as the loading progresses. Therefore, any general formulation of stress-strain relationships for soils clearly must account for the large influence of inherent and induced anisotropy. Casagrande and Carillo (1944) distinguished two forms of anisotropy in soils which they called inherent and induced, respectively. Inherent anisotropy was defined as a “physical characteristic inherent in the material and entirely independent of the applied strains.” Induced
anisotropy was defined as a "physical characteristic due exclusively to the strain associated with the applied stress".

Laboratory studies have demonstrated the inherent anisotropy imparted to granular materials during deposition [Parkin et al. (1968), Arthur and Dunstan (1969), Oda(1972)]. Motivation for modelling induced anisotropy was provided from experimental observations on both sands and clays as reported by a number of researchers [Arthur et al. (1977,1980), Baker and Desai(1984), Mould(1983), Symes et al. (1982), Stipho(1978), Levin(1978)]. The induced anisotropy became apparent especially when the principal stresses were rotated with respect to the material axes. Induced anisotropy was found to have a large influence on the strain required to achieve a given stress ratio and the secant modulus on reloading after a principal stress rotation.

Prevost(1978) formalized Mroz’s(1967) multi-surface model for soils. This model accounts for initial anisotropy and in a limited sense, induced anisotropy. However, contrary to observations this model has the weakness of predicting non-fading anisotropy under continuous isotropic loading. Pietruzack and Mroz(1983) provide for the development and demise of anisotropy by deviatoric translation or rotation of the bounding surface. However no definite procedure is given for the determination of anisotropic parameters. Dafalias(1984) has proposed a varying non-associative flow rule to account for initial and induced anisotropy in cohesive soils during compressive loading. This is achieved by forcing the strain rate tensor to deviate from the normal to the yield surface during the course of plastic deformation. Desai et al. (1986) developed an anisotropic hardening version, $\delta_2$ under hierarchical approach and defined translation rule for induced anisotropy. The effect of induced anisotropy on the response of the material is introduced through deviation from normality to the yield surface of the incremental plastic strains. As the $\delta_1$ model is used herein, its brief description is provided below.
Overview of HISS model

Desai (1980), Desai et al. (1986) have proposed a hierarchy of models with various specialized models, developed in the context of the theory of plasticity. The general category is considered to be the anisotropic hardening model based on the concept of non-associativeness. The simplest case ($\delta_0$ model) involves initially isotropic material, hardening isotropically with associative plasticity. Initially isotropic material hardening isotropically with non-associative plasticity includes effect of factors such as the frictional nature of the material ($\delta_1$ model). $\delta_2$ model describes the behavior of an initially anisotropic material undergoing induced anisotropy during (cyclic) loading, unloading and reloading. Depending upon the complexity of model, the number of constants to be evaluated is also more. In the following section, a brief review of the model is given.

For the basic $\delta_0$ model, $F$ is expressed only in terms of the direct invariants, as

$$F = F(J_I, I_*^I) \quad (2.1)$$

where, $J_i$ (i=1,2,3) are the direct invariants of the stress tensor $\sigma_{ij}$, $I_*^I$ (i=1,2,3) are the direct invariants of the strain tensor, $\epsilon_{ij}$. Equation (2.1) can be written as a (complete) polynomial in $J_1, \sqrt{J_2}$ and $J_3^{1/3}$. The polynomial contains yield functions used in various plasticity models such as Von Mises, Drucker Prager, Mohr Coulomb, Critical State and cap models. With the joint invariants, it can be shown that the nested and boundary surface models are special cases of equation (2.1).

In the HISS model, the yield function is given by (Desai et al. 1986)

$$F = \frac{J_2D}{p_a^2} - \left[ -\alpha \left( \frac{J_1}{p_a} \right)^n + \gamma \left( \frac{J_1}{p_a} \right)^2 \right] (1 - \beta S_r)^m$$

$$F = J_2D - F_b F_s \quad (2.2)$$
where, \( J_{2D} \) is the second invariant of the deviatoric stress tensor, \( S_{ij} \); \( \alpha, \gamma, \beta, \) and \( m \) are the response functions and \( S_r \) is the stress ratio, defined as \( \frac{3}{2J_2^{1/2}} \) and \( p_a \) the atmospheric pressure. The (reference) value of \( m \) is found to be equal to \(-0.5\) for a number of materials. \( F_b \) and \( F_s \) relate to the \( J_1 - \sqrt{J_{2D}} \) and principal stress spaces, respectively, Figure (2.1). Response functions \( \gamma, \beta, (m=-0.5) \) can be assumed to be constants associated with the ultimate surface. \( \beta \) can be assumed to be a constant if the shape of the yield surface is constant. However, for materials like concrete and rock, \( \beta \) can be expressed as \( J_1 \) so that the shape can be allowed to vary with \( J_1 \). For example, it can vary from a triangular shape (with rounded corners) at low values of \( J_1 \) to a circular shape (in limit) at very high values of \( J_1 \).

**Hardening or Growth Function, \( \alpha \)**

The hardening function \( \alpha \) is a function of the trajectory of plastic strains, \( \zeta = \int (\varepsilon_{ij}^p, \varepsilon_{ij}^p)^{1/2}. \) Simple form of \( \alpha \) is given by,

\[
\alpha = \frac{a_1}{\zeta^{\eta_1}}
\]

where \( a_1 \) and \( \eta_1 \) are hardening parameters.

**Non-associative (\( \delta_1 \)) model**

Desai and Siriwardene (1980) proposed the correction function approach for non-associative behavior. Frantziskonis, Desai and Somasundaram (1986) employed the approach to develop the non-associative model, \( \delta_1 \). In the \( \delta_1 \) model the plastic potential function \( Q \) is defined as a modification of the basic isotropic-associative yield function, \( F \),

\[
Q = F + h(J_i, \zeta) \quad i = 1, 2, 3
\]

where \( h \) is the correction factor and \( \zeta \) is the trajectory of plastic strains. Desai et al. (1986) derived the correction function, \( h \), as

\[
h = \left[-(\alpha_Q - \alpha)J_1^n + \gamma J_1^2\right] F_s
\]
where, $\alpha_Q = \alpha + \kappa (\alpha_0 - \alpha)(1 - \zeta_v/\zeta)$, $\kappa$ is a non-associative parameter, $\alpha_0$ is the value of $\alpha$ at the beginning of shear loading, and $\zeta_v$ is the volumetric component of the plastic strain trajectory.

This model was modified by Desai and Wathugala (1987) to incorporate the non-dimensional form of the potential function, $Q$, given by

$$Q = \left[ -\frac{\alpha Q}{(J_1)} \left( \frac{J_1}{P_a} \right) + \frac{(J_1)^2}{(P_a)} \right] F_a$$  \hspace{1cm} (2.6)

**Properties and Advantages of F**

The function $F$ plots as a continuous yield surfaces in various stress spaces (Figure (2.1)) and possesses a number of advantages:

1. It intersects the $J_1$ axis orthogonally which is required for isotropic material undergoing isotropic hardening.
2. For isotropic hardening (isotropic material) it involves only a single surface. Thus, it does not involve singularity at the intersection of failure and yield caps as in other multi-surface models.
3. The final yield surface is termed as the ultimate surface and represents asymptotic stress–strain curves under different stress paths. Hence it includes the special cases such as failure and critical state.
4. It is possible to develop models to account for non associativeness, anisotropic hardening, strain-softening and various effect by using the isotropic hardening as the basic model.
5. It is possible to use the model for materials like concrete and rocks, by incorporating the tension cutoff value in the yield function.

In view of the above attributes, the HISS model is simplified significantly in terms of number of constants, their determination and implementation in (numerical) solution procedures.

2.3 Review on NDT Methods for Material Characterization

The existing NDT methods can be divided into five major categories: Radiographic, Ultrasonic, Acoustic, Magnetic, Electrical and Permeant methods.
Figure 2.1 Schematic of the Yield Function in Various Spaces

[After Desai et al.(1986)]
Each NDT has its own advantages and limitations. The choice of a particular method depends mainly on the information sought in any testing procedure. Most of the NDT results provide qualitative description of the behavior and some quantitative information. Literature survey indicates that only certain of these NDT methods have been used successfully in the case of geologic materials. Since the present study focuses on geologic materials, only the relevant NDT methods are discussed.

Geophysical methods such as crosshole, downhole, surface refraction, and steady-state vibration are commonly used field NDT methods (Stokoe (1972), Ballard (1976), Mooney (1974), Murphy (1972)). These methods are called non-destructive because the in situ observations are made to estimate the shear moduli with very little sample disturbance. Geophysical measurement of the shear wave velocity leads to the estimation of shear modulus. Moduli determined in this manner are commonly referred to as low-amplitude moduli (shearing strains below .001%) and are denoted as $G_{max}$. These moduli are assumed to represent initial tangent moduli used in non-linear stress-strain relations for static and dynamic analyses. A brief explanation of each of these methods is presented below.

**Crosshole seismic survey method (Hoar and Stokoe (1978))**

The crosshole seismic survey method is well suited for determining the variation of in situ shear wave velocity with depth. By this method, the time for body waves to travel between several points at the same depth within a soil mass is measured. Wave velocities are calculated from corresponding travel times once the distance of travel has been determined. The key components in the measurement system of shear wave velocity are: (1) a source which is rich in shear wave generation and weak in compression wave generation and which is directional, repeatable, and reversible, (2) receivers with proper frequency response which are oriented in the direction of S-wave particle motion, (3) a recording system with the proper frequency response with which accurate time measurements can be made and a permanent record produced; and (4) a triggering system which correctly triggers the recorder. One measurement system which fulfills these requirements employs the standard
penetration test (SPT) as the source, velocity transducers with natural frequencies between 4 and 20 Hz as receivers, a storage oscilloscope with camera as the recording system, and a velocity transducer or electrical triggering system.

**Downhole seismic survey method (Hoar and Stokoe (1978));**

The downhole seismic survey method is also well suited for determining the variation of in situ shear wave velocity with depth. With this method, the time for body waves to travel between the surface and points within the soil mass is measured. The key components in the downhole test are the same as in the crosshole test, that is, the source, receivers, recorder, and trigger. One important advantage of this method in comparison with the crosshole test is that only one borehole is required. Available data on the values in situ shear wave velocity over the same travel paths at the same sites by different methods show different values. The reasons for such a scatter could be (Hoar and Stokoe, 1978): (1) improper generation and sensing of shear waves. (2) poor quality control, and (3) use of poorly trained and poorly supervised personnel.

Drnevich et al. (1978), developed ‘Resonant-Column Method’ to determine the shear modulus, shear damping and Young’s modulus as functions of vibratory strain amplitude and other factors such as ambient confining stress and void ratio. The test is conducted on solid cylindrical undisturbed and remolded samples.

Hardy (1981), presented a state-of-the-art paper on application of ‘Acoustic Emission (AE)’ techniques to rock and rock structures. This paper also describes the use of AE in laboratory evaluation of in situ stresses, evaluating effects of blasting, hydro-fracturing, monitoring coal mines and so on. The main difference between the ultrasonic and acoustic emission methods is that in the ultrasonic method, ultrasonic signals that are generated externally are passed through the material under investigation and received. The received signal is affected by the stress and the basic characteristics of the material. In contrast, in the acoustic emission method, self-generated signals occurring within the material are received by one or more receiving transducers.
Acoustic emission techniques are relatively recent additions to the testing of soils dating back to the beginning of 1970's. However, in the past three decades, interest has been generated in the soils area to the point where equipment manufacturers are currently marketing acoustic emission systems specifically for geotechnical applications. The state-of-the-art paper by Koerner et al. (1981) on acoustic emission activity on soils presents the basic fundamentals, small-scale as well as large-scale laboratory tests. Furthermore, the technique has been applied to field situations in a number of cases, like slope stability monitoring of dams and embankments, soil movements arising from horizontal and vertical deformations, seepage monitoring, and grout/hydro-fracture monitoring. In some of these cases, it is possible to assess the actual stress levels in a given situation.

Studies by Tanimoto and Nakamura, (1981), on AE in soils reveal that under both strain-controlled and stress-controlled triaxial tests, characteristics of AE are closely connected with the rate of axial strain, the point of dilatancy, and work done by external stresses during shear process. The tests also revealed that a correlation exists between AE characteristics and the (shear) stress-deformation properties of soils.

2.4 Review on Ultrasonic Testing

This section is divided into two parts. The first part deals with the basic principles of ultrasonics, While the second part gives the review of literature in which ultrasonic techniques are used for material characterization.

2.4.1 Basic principles of ultrasonic testing

Ultrasonics is one of the NDT methods which can be used to obtain quantitative information about the material characterization (Krautkramer, 1983). Any sound wave whose frequency is higher than 20 KHz. is called ultrasonic. Normally, the frequency range used in any ultrasonic testing is in the range of 0.5 - 10 MHz.

Figure (2.2) shows a setup for an ultrasonic measurement. It consists of a pulse generator, a transmitting transducer, which converts electrical energy to
Figure 2.2 Schematic of Ultrasonic Testing
mechanical energy, a receiver which converts the received mechanical vibrations into electrical pulse, and an oscilloscope for observing the received signal. The display seen on the oscilloscope is called ultrasonic wave signature. A great deal of information about the internal changes of a material can be inferred by observing the wave signature. Since the probe is outside the specimen to be tested, it is necessary to provide a coupling agent between the probe and the specimen. The couplant, a liquid or pliable solid, is interposed between the probe surface and the specimen surface, in order to assist the passage of the ultrasonic energy.

The nature of ultrasonic waves is such that propagation involves particle motion in the medium through which they travel. The propagation may be by way of a volume change, the compression wave form or by a distortion process, or by the shear wave form. The speed of propagation thus depends on the (elastic) properties and the density of the particular medium. When an ultrasound wave meets an interface of two media, some of the wave is reflected, the amount depending on the acoustic properties of the two media and the direction governed by the same laws as for light waves. Energy may be lost or attenuated during the propagation of the ultrasound due to energy absorption within the medium and to scatter which results from interaction of waves with microstructural features of size comparable with the wavelength.

The wavelength determines the defect sensitivity in that any defect dimensionally less than half the wave length will not be detected. Consequently, the ability to detect small defects increases with decreasing wave length of vibration and, since the velocity of sound is a characteristic of a particular material, (for geologic materials like rock and concrete the wave speed is approximately 0.5 m/sec) increasing the frequency of vibration will provide the possibility of increased sensitivity. Frequency selection is thus a significant variable in the ability to detect small cracks.
Ultrasonic transducers

Ultrasonic waves are generated in a transducer mounted on a probe. The transducer material has the property of expanding and contracting under an alternating electrical field due to the piezoelectric effect. Probes may generate either compression waves or angled shear waves, using either single or twin piezoelectric crystals. It can thus transform electrical oscillations into mechanical vibrations and vice-versa. The probe may be used to transmit energy as a transmitter, receive energy as a receiver or transmit and receive as a transceiver. In the following section, a brief description of the factors which influence the selection of the appropriate transducers are given:

1. Crystal materials: Materials such as quartz and ceramics possess piezoelectric properties. A desirable crystal characteristic is a short ringing time. Ringing time is the time period involved in the decay of crystal vibrations after the initial excitation of the crystal. However, crystals with short ringing times have lower sensitivity than those with longer ringing times. Also, crystals with low Poisson’s ratio will vibrate effectively in the compressional mode and less in the distortional modes.

2. Directional characteristics: The amount of mode conversion at the probe-specimen interface is related to the crystal size and wavelength of the specimen. The wavelength-to-diameter ratio of a particular crystal controls the intensity of secondary waves transmitted into the specimen. It is observed that for testing techniques where the existence of strong secondary waves can be a hindrance, the wavelengths of the compressional wave in the specimen should be considerably smaller than the crystal diameter. The diameter of the crystal should be chosen large enough so that the divergence of the ultrasonic beam is minimized.

3. Near-field effects: The amount of mode conversion can also be decreased by choosing larger-diameter crystals. The choice of a large-diameter crystal increases the length of the field while simultaneously decreasing the amount of mode conversion from reflections at the specimen boundaries.
4. Infinite media assumption: To assume "infinite media" or to be able to ignore the effects of specimen size, the wavelength of the ultrasonic pulse in the specimen should be as small as possible compared to the specimen dimensions. This criterion sets an upper limit of wavelength for a particular-size specimen. For a material with known velocity, this maximum wavelength corresponds to a minimum crystal frequency according to the equation

\[ \lambda_{\text{max}} = V T_{\text{max}} = \frac{V}{f_{\text{min}}} \]

where, \( \lambda_{\text{max}} \) = the required maximum wavelength of the crystal in order to satisfy the assumption of an 'infinite media', \( V \) = wave velocity in the material being tested, \( T_{\text{max}} \) = period length corresponding to \( \lambda_{\text{max}} \), and \( f_{\text{min}} \) = minimum frequency corresponding to \( \lambda_{\text{max}} \).

5. Material grain size: Scattering of the ultrasonic wave increases greatly as the wavelength in the specimen approaches the grain diameter of the specimen. A minimum wavelength acceptable for testing in a particular material is thus set by the grain diameter. By using the expression given above, the maximum frequency is calculated corresponding to the minimum wavelength set by the grain size.

6. Quality factor (\( Q_f \)): The quality factor is defined as the ratio of the resonant frequency to the bandwidth between the half-power points. It is also linked to the logarithmic decrement(\( \delta \)) by, \( Q_f = \pi/\delta \). A very convenient definition for use in the time domain states that the number of cycles required for the pulse to ring down to 4% of its original amplitude is equal to the \( Q_f \) of the transducer. For example, a transducer with a \( Q_f \) of 100 will resonate for just 100 cycles before dying out. Also, low value of \( Q_f \) corresponds to a low pulse length and vice versa.

Relation between elastic constants and ultrasonic velocities

Birch(1960) has given the relations between the elastic moduli and the velocity of ultrasonic waves for an isotropic and unstressed material. Table (2.1) shows these expressions. ASTM d2845-83 (1984) describes a standard method for the laboratory determination of pulse velocities and ultrasonic constants for rock.
### Table 2.1 Relation Between Elastic Constants and Ultrasonic Velocity

<table>
<thead>
<tr>
<th>Variables</th>
<th>Bulk Modulus $K$</th>
<th>Young's Modulus $E$</th>
<th>Lame's Constant $\lambda$</th>
<th>Poisson's Ratio $\sigma$</th>
<th>Longitudinal Modulus $L$</th>
<th>Shear Modulus $G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho, V_p, V_s$</td>
<td>$\rho [V_i^2 - (4/3) V_s^2]$</td>
<td>$\rho V_i^2 \frac{(3 V_i^2 - 4 V_s^2)}{V_i^2 - V_s^2}$</td>
<td>$\rho (V_i^2 - 2 V_s^2)$</td>
<td>$\frac{V_i^2 - 2 V_s^2}{2} (V_i^2 - V_s^2)$</td>
<td>$\rho V_i^2$</td>
<td>$\rho V_s^2$</td>
</tr>
<tr>
<td>$\lambda, G$</td>
<td>$\lambda + (2G/3)$</td>
<td>$G \frac{3\lambda + 2G}{\lambda + G}$</td>
<td>$\ldots$</td>
<td>$\frac{\lambda}{2(\lambda + G)}$</td>
<td>$\lambda + 2G$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$K, \lambda$</td>
<td>$\ldots$</td>
<td>$\frac{K - \lambda}{3K - \lambda}$</td>
<td>$\ldots$</td>
<td>$\frac{\lambda}{3K - \lambda}$</td>
<td>$3K - 2\lambda$</td>
<td>$\frac{3(K - \lambda)}{2}$</td>
</tr>
<tr>
<td>$K, G$</td>
<td>$\ldots$</td>
<td>$9K \frac{KG}{3K + G}$</td>
<td>$K - (2G/3)$</td>
<td>$\frac{3K - 2G}{2(3K + G)}$</td>
<td>$K + (4G/3)$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$E, G$</td>
<td>$EG/3 (3G - E)$</td>
<td>$G \frac{E - 2G}{3G - E}$</td>
<td>$(E/2G) - 1$</td>
<td>$G \frac{4G - E}{3G - E}$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$K, E$</td>
<td>$\ldots$</td>
<td>$3K \frac{3K - E}{9K - E}$</td>
<td>$\frac{3K - E}{6K}$</td>
<td>$\frac{3K + E}{9K - E}$</td>
<td>$\frac{3KE}{9K - E}$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$\lambda, \sigma$</td>
<td>$\lambda [1 + \sigma/(3\sigma)]$</td>
<td>$\lambda \frac{(1 + \sigma)(1 - 2\sigma)}{\sigma}$</td>
<td>$\ldots$</td>
<td>$\frac{\lambda (1 - \sigma)}{2\sigma}$</td>
<td>$\lambda$</td>
<td>$\frac{1 - 2\sigma}{2\sigma}$</td>
</tr>
<tr>
<td>$G, \sigma$</td>
<td>$G[2(1 + \sigma)/(3(1 - 2\sigma)]$</td>
<td>$G \frac{2\sigma}{1 - 2\sigma}$</td>
<td>$\ldots$</td>
<td>$G \frac{2 - 2\sigma}{1 - 2\sigma}$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$K, \sigma$</td>
<td>$\ldots$</td>
<td>$3K \frac{\sigma}{1 + \sigma}$</td>
<td>$\ldots$</td>
<td>$3K \frac{1 - \sigma}{1 + \sigma}$</td>
<td>$\frac{3K (1 - 2\sigma)}{2 + 2\sigma}$</td>
<td>$\ldots$</td>
</tr>
<tr>
<td>$E, \sigma$</td>
<td>$E/[3(1 - 2\sigma)]$</td>
<td>$E \frac{(1 + \sigma)(1 - 2\sigma)}{\sigma}$</td>
<td>$\ldots$</td>
<td>$E (1 - \sigma)$</td>
<td>$E$</td>
<td>$\frac{1}{2 + 2\sigma}$</td>
</tr>
</tbody>
</table>

Note: $V_i$ = P-wave Velocity  
$V_s$ = Shear-wave Velocity
In this method a rock sample of standard dimension is tested in three orthogonal directions using the ultrasonic testing equipment. The initial anisotropy is reported in terms of the variation of wave velocity in three directions.

It is observed that the velocity of elastic waves is dependent on the stress state within the material. By using the finite strain formulations of Murnaghan (1951), Hughes and Kelly (1953) obtained seven expressions for the stress dependence of the velocities of principal ultrasonic waves in initially isotropic materials, two of the expressions relating to the hydrostatic pressure, and the other five to simple cases of an applied uniaxial stress.

\[
\rho_0 V_{lp}^2 = \lambda + 2\nu - \frac{P}{3K_0} (7\lambda + 10\nu + 6l + 4m) \tag{2.7a}
\]
\[
\rho_0 V_{sp}^2 = \nu - \frac{P}{3K_0} \left(3\lambda + 6\nu + 3m - \frac{n}{2}\right) \tag{2.7b}
\]
\[
\rho_0 V_{lx}^2 = \lambda + 2\nu + \frac{T}{3K_0} \left(\frac{\lambda + \nu}{\nu} (4\lambda + 10\nu + 4m) + \lambda + 2l\right) \tag{2.7c}
\]
\[
\rho_0 V_{sx}^2 = \nu + \frac{T}{3K_0} \left(4\lambda + 4\nu + m + \frac{\lambda n}{4\nu}\right) \tag{2.7d}
\]
\[
\rho_0 V_{ly}^2 = \lambda + 2\nu - \frac{T}{3K_0} \left(\frac{2\lambda}{\nu} (\lambda + 2\nu + m) - 2l\right) \tag{2.7e}
\]
\[
\rho_0 V_{sy}^2 = \nu + \frac{T}{3K_0} \left(\lambda + 2\nu + m + \frac{\lambda n}{4\nu}\right) \tag{2.7f}
\]
\[
\rho_0 V_{sz}^2 = \nu - \frac{T}{3K_0} \left(2\lambda - m + .5n + \frac{\lambda n}{2\nu}\right) \tag{2.7g}
\]

where, \(\rho_0\) is the density of the material in unstrained state, \(V\) is the velocity of the ultrasonic wave, \(\lambda\) and \(\nu\) are the second order Lame's constants for an isotropic material, \(l, m, n\) Murnaghan third-order elastic constants for an isotropic material, \(P\) is the hydrostatic stress, \(T\) is the uniaxial tension and \(K_0\) is the bulk modulus.

The first subscript to the velocity squared terms indicates the nature of the wave motion, that is, longitudinal (l) or shear (s). The second subscript indicates the type and direction of the applied stress, that is, hydrostatic pressure (p), uniaxial tension in the y-direction (y) and tension in the z-direction (z).
Truesdell (1962) derived quantitative expressions for the velocities of principal elastic waves in isotropic solids under finite elastic strain. In his paper he proposed an universal criterion for the existence of a strain-energy function according to the second-order approximation. The expression involved the strains and the velocities of the compression and shear waves.

2.4.2 Ultrasonic method for material characterization

There is a large body of literature available on application of ultrasonic techniques. This includes material characterization at a microscopic level and also macroscopic level. In the study presented herein, only those references which are directly relevant are considered. These include, studies on the influence of externally applied loads (stresses) on ultrasonic properties and their effects like stress-induced anisotropy and damage.

Several investigators have studied the effects of stress-induced anisotropy on the propagation of ultrasonic waves (Ensminger, 1988). Most of the proposed techniques are in the development stage and have been used primarily in laboratories. Change in the velocity with change in stress in metals is small, and many other factors also affect the velocity by amounts that may obscure stress-induced changes.

Roesler (1979), used the idea of measuring the shear wave velocity through sand specimens to define stress anisotropy and its effect on shear moduli. He conducted NDT and mechanical tests for different stress paths and observed that

1. The velocity of the shear wave increases with the mean stress.
2. The shear wave velocity depends on the nature of stresses and the mode of deformation of the sand.
3. Stress anisotropy can be captured by rotating the direction of polarization of shear waves.

In a recent study by Sayers et al. (1990), on stress induced ultrasonic anisotropy in Berea sandstone has revealed that changes in the velocity of ultrasonic waves can be used as a measure for quantifying initiation and distribution of
micro-cracks. They observed a considerable change in velocities upon loading up to failure in a triaxial test.

Bergman and Shahbender (1958), measured fractional changes in the velocity of both longitudinal and shear waves propagated across aluminium bars subjected to static axial stresses. The carrier frequency of the ultrasonic pulses was 5 MHz and the experimental arrangement enabled small changes in the velocities to be determined by a simple differential method. In their experiments, changes in pulse transit time in the loaded aluminium sample were measured by comparison with the arrival time of a similar pulse propagated across an identical unstressed column. The pulse-echo patterns corresponding to stressed and unstressed samples were displayed simultaneously on a twin-channel oscilloscope. The largest changes in velocity occurred for shear waves polarized parallel to the direction of applied stress. Measurements were extended well into the plastic region with the interesting result that the velocity of the shear wave in the direction of the applied load remained almost constant at its yield point value.

Shah and Chandra (1970), examined the mechanical behavior of concrete using ultrasonic measurements. In their study, the velocity and attenuation of ultrasonic pulses transmitted across concrete and paste specimens subjected to various mechanical loads were measured and compared with surface strains and internal micro-cracking. For monotonically increasing loading of concrete specimens, it was observed that prior to failure, pulse velocity and amplitude started to continuously decrease and volume started to dilate, indicating the internal crack growth. However, no such changes were observed for hardened paste specimens.

Jones (1956), used ultrasonic pulse measurements to study the rate of hardening of soil-cement. In this technique, the velocity of propagation of a pulse through the soil-cement is measured and its increase as the mixture ages indicates the hardening that occurs. The test was repeated for various types of sands and the same trend was observed. For the particular soil-cement tested, the compressive strength ($C$) and pulse velocity ($V$) were related by an expression of the form, $C = a V^3$, where, 'a' is a parameter.
Raju (1970), reported laboratory tests on prismatic concrete specimens under uniaxial compression with static and repeated loadings. In his study, the ultrasonic pulse velocity was used to quantify the micro-crack growth in high-strength concrete. Following conclusions were made:

1. A significant decrease in the pulse velocity occurs in the lateral and longitudinal directions for concrete specimens subjected to repeated compressive loads of intensity 65 to 85 % of the static ultimate strength.

2. The magnitude of decrease in the pulse velocity in the lateral direction under repeated compressive loads is nearly three times greater than that under static loads.

3. The pulse velocity decreases with fatigue life at an increasing rate, and an empirical relation established between the parameters can be used to estimate the remaining fatigue life of a partially fatigued specimen.

Suaris and Fernando (1987), performed cyclic loading test combined with ultrasonic tests on concrete cylindrical [3 in. (75 mm) dia., 6 in. (150 mm) height] specimens. The tests were repeated for various mixes of concrete. The purpose of their research was to quantify the damage growth of concrete using the ultrasonic attenuation as a guideline. The results obtained from monotonic and cyclic compression tests showed that the ultrasonic attenuation can be used to effectively monitor the crack growth that occurs. It was observed that the amplitude of attenuation of the waveform was much more sensitive to crack growth than the widely used pulse velocity technique. The tests also revealed that the use of pulse velocity equipment without an oscilloscope may lead to erroneous results because of the very high attenuation of the normal transducer frequency near failure. The results from cyclic loading tests showed that damage accumulation as measured by pulse attenuation is not linear, particularly during the initial cycles.

Varadarajan and Desai (1987) used ultrasonic tests on rock salt (cubical) samples and their experiment shows that there is a considerable change in the velocity and amplitude of P-waves, before (that is stress free state) and after (that is failure state) the test (Table (2.2)).
Table 2.2 Ultrasonic Test Results for Rock Salt Specimens
[Varadarajan and Desai(1987)]

<table>
<thead>
<tr>
<th>Test</th>
<th>Direction</th>
<th>Nature of dimension change during shear</th>
<th>Velocity $10^5$ m/sec</th>
<th>Amplitude of wave in volts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before test</td>
<td>After test</td>
</tr>
<tr>
<td>CTC</td>
<td>xx</td>
<td>increase</td>
<td>27.58</td>
<td>26.21</td>
</tr>
<tr>
<td></td>
<td>yy</td>
<td>increase</td>
<td>28.22</td>
<td>26.89</td>
</tr>
<tr>
<td></td>
<td>zz</td>
<td>decrease</td>
<td>25.78</td>
<td>26.15</td>
</tr>
<tr>
<td>TE</td>
<td>xx</td>
<td>decrease</td>
<td>27.17</td>
<td>25.81</td>
</tr>
<tr>
<td></td>
<td>yy</td>
<td>decrease</td>
<td>26.32</td>
<td>25.87</td>
</tr>
<tr>
<td></td>
<td>zz</td>
<td>increase</td>
<td>27.36</td>
<td>25.76</td>
</tr>
</tbody>
</table>
It was observed that the velocity and amplitude increased or decreased depending on whether the dimensions of the sample decreased or increased, respectively. However, the available data was limited and no attempt was made to observe the ultrasonic characteristics during the test process.

Use of P-waves to describe the anisotropic nature of earth’s crust has been reported by a number of investigators in the area of Geophysics [Bamford and Crampin (1977), Crampin et al. (1984)]. Here the term anisotropy is used to describe the variations in the value of P-wave velocity at any given point in different directions. Such an anisotropy has been attributed to the preferred orientation of crystals, presence of grains and cracks, and due to layering or lamellation. Figure (2.3a) shows the variation of P-wave velocities in the upper mantle of the Pacific ocean (Hess (1964)) with the azimuth. This study, showed a connection between the anisotropy and spreading of the sea-floor since the direction of smallest velocity was perpendicular to the large fracture zone. Similar variation in the azimuthal dependence of P-wave velocities near Hawaii has been reported by Morris et al. (1969) (Figure (2.3b)).

Field measurement of P-wave velocities has been reported by Silaeva (1984). In this paper, in situ measurements of velocity has been reported in the zone of Karasuisk overthrust near the Toktogul hydroelectric station. Observations made between 1963-1980, indicate that the velocity anisotropy is dependent the state of stress of the rock mass. Figure (2.4a) shows the section along the tunnel at the Tokotogul reservoir, and site of ultrasonic observations. Ultrasonic observations were made at five chambers lying at 250m (CH 2), 930m (CH 9), 1100m (CH 11), 1400m (CH 14) and 2400m (CH 24) from the entrance to the tunnel. There is a fracture zone at the entrance of the tunnel. Figure (2.4b) show the variation of change in transit time to the original transit time ($\Delta t/t_0$) along x, y and z directions for a period of 1975-1980. This shows that the velocity of P-waves is indeed a function of state of stress within the rock.
Figure 2.3a Variation of P-wave Velocities in the Upper Mantle of the Pacific Ocean [After Hess (1964)]

Figure 2.3b Variation of P-wave Velocities near Hawaii [After Morris et al. (1969)]
Figure 2.4  Field Observations of Ultrasonic Velocities adjacent to a Tunnel [After Silaeva (1984)]
CHAPTER 3

DESCRIPTION OF RESEARCH

3.1 General

Some geologic materials when subjected to sequences of loading, unloading and reverse loading, exhibit induced anisotropic response. In the literature, it is often called stress induced anisotropy and is attributed to reorientation of particles and to the formation of micro-cracks and damage. As the stress induced anisotropy is essentially due to the stresses (caused by external mechanical loads), we can call this form of anisotropy as "Mechanical Anisotropy". Some of the available constitutive laws can quantify the mechanical anisotropy and a few qualitatively describe the anisotropic response. However, for better understanding of the internal changes occurring in a material and to obtain a physical measure of induced anisotropy, alternative testing procedures, such as ultrasonic technique are desirable. Thus, in the current study, a combination of mechanical (destructive) and ultrasonic (non-destructive) testing procedures are used, for the enhanced understanding of the phenomenon of induced anisotropy.

The proposed mechanical and ultrasonic measurements, as described subsequently, are performed while test samples are subjected to loading under various stress paths in the modified truly triaxial device. Ultrasonic P-waves pass through a sample of a geologic material in the X, Y and Z directions in the through-transmission mode, and the received signals are recorded. The stress-strain, stress-velocity and stress-attenuation (defined below) data are examined to understand the response of the material and to obtain the correlation functions for the stress-induced anisotropy.

3.2 Mechanics of Proposed Method

Figure (3.1) shows a schematic of the proposed ultrasonic testing. A cubical sample of the material of dimensions $L_x \times L_y \times L_z$ is enclosed within the
modified truly triaxial device. \( T_x, T_y, T_z \) are the transmitting transducers which send in a negative spike pulse of known amplitude through the sample in the X, Y, and Z directions, respectively. After travelling through the sample, the pulse is received by receiving transducers \( R_x, R_y, R_z \), respectively. Figure (3.1) also shows the schematic output wave signatures in the three directions as recorded by the oscilloscope. The wave signature in any given direction is entirely dependent upon the stress state within the material and it qualitatively describes the physical state of the material. These wave signatures show an initial peak and attenuates gradually. This is because, the ultrasonic signal looses energy as it travels through the material. In the proposed tests, the sample is subjected to stresses along different stress paths in loading, unloading and reloading. At each stress level, the deformations are recorded by LVDTs, and the P-wave signatures in three principal directions by the oscilloscope. The change in LVDT readings can be used to compute strains, and can be used to define and quantify the mechanical anisotropy.

Consider the wave signatures in the X, Y and Z directions as shown in Figure (3.1). The time between the initiation of the wave and the first peak in any given direction is defined as th transit time in that direction. The transit time is generally expressed in terms of \( \mu \)sec. In Figure (3.1), \( t_x, t_y \) and \( t_z \) represents the transit time in the X, Y, and Z directions, respectively. The ratio of the transit time to the specimen dimension in any given direction corresponds to the velocity of the material in that direction. The velocity of the P-wave in the \( i \)th direction is represented by \( V_i \) [\( V_i = L_i/t_i, (i=X, Y, \text{ and } Z) \)], and is related to the relative orientation of the particles in that direction. Application of external stresses results in change in specimen dimensions. However, as those changes are infinitesimal (small strains), we can compute the velocity based on the initial dimensions of the sample, namely \( L_x, L_y \) and \( L_z \).
Figure 3.1 Schematic of Multi-Axial Ultrasonic Testing
As the ultrasonic wave travel in the $i$th direction, its energy decreases because of scattering through the micro-cracks and micro-voids within the material. This loss of energy is related to the attenuation ($A_i$) of the wave in the $i$th direction,

$$A_i = 20 \log \left( \frac{\text{output voltage}}{\text{input voltage}} \right)$$

$$A_i = 20 \log \left( \frac{a_i}{a_0} \right)$$

(3.1)

where $a_i$ is the absolute maximum value of amplitude of the wave signature in the $i$th direction (Figure 3.1) and $a_0$ is the input voltage, obtained from the instructions manual of the pulser/receiver (explained later) unit. Thus, $V_i$ and $A_i$ define the physical state of the material at any stress state. Therefore, the velocity and amplitude attenuation can be used to define and to quantify the physical measure of anisotropy. Instead of using the absolute changes in the values of voltage and amplitude (which are relatively small), a non-dimensional or relative change in velocity and attenuation can be defined. Further, by observing the test results on a number of samples under varieties of stress paths, a suitable physical measure of anisotropy can be obtained. This physical measure is compared with the mechanical anisotropy, and suitable correlation functions are postulated.

3.3 Ultrasonic and Mechanical Testing

Figure (3.2) shows the setups for ultrasonic and mechanical testings. It consists of the truly triaxial device, which needs to be modified, an ultrasonic unit and a data acquisition system. In the following sections, brief descriptions of the instrumentation and the procedure for the sample preparation are given:

3.3.1 Ultrasonic device:

This ultrasonic device (Figure (3.2)) is a broadband ultrasonic pulser/receiver unit supplied by the Panametrics Inc. This unit has two-pole, three-position manual coaxial switch and ports for transducer connections. The unit provides a digital output of the transit time (in $\mu$sec) of P-waves through the sample.
Figure 3.2 Setup for Ultrasonic and Mechanical Testing
The unit sends in a ‘negative spike’ input pulse of variable intensity and duration.

**HP 54501A Oscilloscope:**

The received pulse from the pulser/receiver unit can be viewed on an oscilloscope. The oscilloscope is portable and programmable. The oscilloscope is connected to the central data acquisition and control unit. The output signature is digitized and stored in the HP 300 computer. Thus, it enables on-line monitoring of the entire experiment.

**VT - 101 Transducers:**

In the present study, transducer of 1.25" (31.25 mm) diameter and 0.63" (15.75 mm) thick, with a frequency of 0.5 MHz. has been used. In the following section, check for the suitability of transducers for testing is given.

It is observed that transit time through a 4.0" (100 mm) material under consideration varies between 40 to 200 µ sec., depending on its constituents. This corresponds to a velocity of $100 \times 10^3$ in/Sec ($2.5 \times 10^6$ mm/sec) to $20 \times 10^3$ in/sec ($0.5 \times 10^6$ mm/sec) and a wave length of $0.2"$ to $0.04"$ (5 mm to 1 mm). Note that the velocity in a weaker material is smaller than that in a stronger material.

1. To limit the intensity of shear waves, the wavelength of the P-waves should be much smaller than the transducer radius, or $\lambda << 2a$, where $a =$ radius of the transmitting crystal = $0.625"$ (15.625 mm) In the present case the largest $\lambda$ (0.2" or 5 mm) is much smaller than $2a$ (1.25" or 31.25 mm). Thus the transducer radius satisfies the required condition.

2. To assume “infinite media” we need to satisfy the condition, $\lambda << L_p$, where $L_p$ is the length of the specimen perpendicular to the wave propagation direction. This condition is also satisfied since the largest $\lambda$ (0.2" or 5 mm) is much smaller than $L_p$ (4" or 100 mm).

**3.3.2 Modification of the multi-axial device:**

Existing truly triaxial device has a cavity of $4" \times 4" \times 4"$ (100 x 100 x 100 mm), in which the cubical specimen is placed. The sample is stressed in three
principal directions using air pressure, contained by rubber membranes. The deforma-
tions of the sample are measured using Linear Variable Differential Transformers
(LVDTs) in three principal directions. This device needs to be modified for per-
forming the ultrasonic testing in combination with the mechanical testing.

Figure (3.3) shows the schematic for installing the transducers in the cubical
device. The transducers are pressed against the face of the specimen on all the six
faces, and the contact is ensured by applying copious supply of vacuum grease (Dow
Corning grease), and through connection to a pre-compressed spring. In order to
make the ultrasonic measurements, during the deformed state, the transducers are
housed in a special device. This device consists of a core and a sleeve made up
of a smooth material. The core houses the transducer and moves inside a smooth
sleeve during the specimen deformation. The base of the core is supported by a pre-
compressed spring of very low stiffness, so as to ensure proper contact between the
sample and the transducer (Figure (3.4)). The outer sleeve is connected to the base
plate of the cubical device by screws and is placed concentric with the other three
(existing) LVDTs on each face (Figure (3.5)). A special connector is used to carry
the co-axial cable of the transducer through the end cap of the LVDT protection
cylinder.

### 3.3.3 Data acquisition system

The data acquisition system consists of a HP 9000 model 300 series computer,
a HP 3852A mainframe controller and a power supply for 18 modified Schaevitz
GCA-121-250 LVDTs. During a test, the controller takes the voltage readings from
the power supply, digitized waveform from the oscilloscope and transfers the data
on to the computer. All the instruments are communicated through the computer,
by running the data acquisition program (written in BASIC).

### 3.4 Material and Sample Preparation

The geologic material used in this investigation consists of a cemented sand.
The cemented sand has been selected for two reasons:
Figure 3.3 Exploded View of the Cubical Device and Details of Mounting
Figure 3.4 Details of VT-101 Transducer Mounting

Figure 3.5 Assembled View of VT-101 Transducer
(a) a purely granular material enclosed in a rubber membrane causes scattering of ultrasonic waves, and (b) a cemented sand imparts cohesion which keeps the sample stable and intact and permit passage of the waves with very little scattering. The sample is $4 \times 4 \times 4''$ $(100 \times 100 \times 100 \text{ mm})$ size and consists of Leighton-Buzzard sand, 5% by weight of Burke stone (quick setting cement) and 14% by weight of water. Dry sand, cement and water are mixed thoroughly in a tray and the mixture is placed in a cubical mold (Figure 3.6). The inner surface of the mold is greased before adding the mixture. The mixture is then compacted in four equal layers using a compacting rod. The mold is removed after 24 hours and a thin coat of quick cement paste is applied on all faces, to insure a smooth surface for ultrasonic testing. Figure 3.7 shows a cured specimen ready to use in the multi-axial device.
Figure 3.6 Accessories for Sample Preparation
Figure 3.7 Cured Cemented Sand Sample
CHAPTER 4

ULTRASONIC AND MECHANICAL TESTING PROGRAM

4.1 General

This chapter gives the details regarding the types of tests performed, testing procedure, test results and definitions of anisotropy. As mentioned in Chapter 3, proposed experimental scheme involves multi-axial mechanical (destructive) and ultrasonic (non-destructive) tests.

4.2 Testing Procedure

4.2.1 Types of tests

The standard tests used under the present investigation are the hydrostatic compression (HC), conventional triaxial compression (CTC), reduced triaxial extension (RTE), triaxial compression (TC) and triaxial extension (TE). Figure (4.1) shows the stress paths along which the cubical samples are tested. In the following sections, these tests will be referred to by their respective abbreviations. During the shear phase of loading, in each of the tests, the sample is subjected to cycle(s) of loading, unloading and re-loading. Some special tests are also performed in which, during the shear phase of loading, a small hydrostatic stress [1psi (6.89 kPa)] was applied and removed, in order to capture the effect of induced anisotropy. In each of the tests, the sample is transferred to the apparatus in such a manner that the vertical direction during sample preparation coincides with the vertical Z-direction of the apparatus. Also, the principal directions of loading and deformations are defined to coincide with each other. Further, in each of the tests, the strains and velocities in the three directions are computed based on the un-deformed (initial) dimensions of the sample, assuming the validity of the small strains theory.
<table>
<thead>
<tr>
<th>Test #</th>
<th>Type</th>
<th>Stress Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HC</td>
<td>Hydrostatic test with confining pressures up to 120 psi</td>
</tr>
<tr>
<td>2</td>
<td>CTC20</td>
<td>CTC test with confining stress of 20 psi, with 1 psi confining stress at various points along the stress path</td>
</tr>
<tr>
<td>3</td>
<td>CTC30</td>
<td>CTC test with confining stress of 30 psi, with 1 psi confining stress at various points along the stress path</td>
</tr>
<tr>
<td>4</td>
<td>TE45</td>
<td>TE test with confining stress of 45 psi</td>
</tr>
<tr>
<td>5</td>
<td>TC30</td>
<td>TC test with confining stress of 30 psi</td>
</tr>
<tr>
<td>6</td>
<td>TE30</td>
<td>TE test with confining stress of 30 psi</td>
</tr>
<tr>
<td>7</td>
<td>CTC10</td>
<td>CTC test with confining stress of 10 psi</td>
</tr>
</tbody>
</table>

Figure 4.1 Proposed Laboratory Stress Paths
4.2.2 Calibration of the ultrasonic device

A steel test piece [4" (100 mm) long and 1.5" (37.5 mm) dia.], for which the exact transit time of the P-wave is known, is selected. The test piece is placed between a pair of transducers and the test is performed in the through-transmission mode (Figure 4.2). The resulting transit time, as displayed by the pulser/receiver unit is matched with the exact transit time (20.35 µsec), by adjusting the zero adjustment knob.

4.2.3 Calibration of the cubical device

As mentioned in Chapter 3, the existing Cubical device needs to be modified for the installation of ultrasonic transducers. Presence of these transducers, coaxial with the existing LVDTs, might create some extra stiffness on the sides of the sample being tested. In order to verify the influence of the (presence of) ultrasonic transducers on the displacement of LVDTs, tests were conducted on a rubber cube. A rubber cube was placed in the cavity centrally, stresses are applied and deformation of LVDTs are recorded. The test is performed with and without installing ultrasonic transducers. Plots of stress versus displacement (Desai and Jagannath, 1991), showed that the presence of ultrasonic transducers had insignificant influence on the deformation of the sample, as measured by LVDTs. Further, each of the 18 LVDTs is calibrated using a standard load cell of the MTS device, in order obtain the calibration constants for converting voltage to the displacement.

4.2.4 Specimen installation and testing

The prepared sample is installed in the cubical cavity of the reaction frame with flexible membranes on each side. A uniform (normal) stress on each face of the soil sample is applied by pneumatically pressurizing the membranes. The applied pressure in each of the three directions is controlled independently. The air pressure system consists of an air compressor, pressure regulators and Bourdon tube gages. The loading is quasi-static. Deformations of the sample are measured by means of LVDTs. An unique feature of the data acquisition unit is that at the end of the experiment, both mechanical (stress and deformation) and ultrasonic
Figure 4.2 Calibration of the Ultrasonic Unit
(wave signatures and velocities) data are available in respective files for further analysis. Figure (4.3) show the Flow Chart of the data acquisition program and the schematic of testing procedure.

4.3 Test Results

In this section, test results on cemented sand under various stress paths are presented.

4.3.1 HC test

Here, test results corresponding to the hydrostatic loading are presented. In this test, the confining pressure is applied in small increments up to a maximum of 120 psi (827 kPa). During the test, the sample is subjected to two cycles of loading, unloading and re-loading. At each stress level, the strains in the material, and the ultrasonic wave signatures are recorded. The wave signatures are used to compute the velocity and the attenuation of the P-wave through the sample.

Figure (4.4) shows the plot of confining stress versus the strains during the HC test. It can be seen that for any given confining stress, the strains, $\epsilon_x$, $\epsilon_y$ and $\epsilon_z$ are different, indicating that the material is anisotropic. This behavior is attributed to the initial anisotropy of the material, due to sample preparation procedure. Further, at very large values of confining pressures, it is observed that the incremental strains with applied confining pressure remains almost the same. This is because, the material becomes less anisotropic at very high confining pressure.

Figure (4.5) show the variation of velocities ($V_x$, $V_y$ and $V_z$) with confining pressure. It is observed that the velocities in three directions are different at zero confining pressure, clearly showing the presence of initial anisotropy. A close look of the values of velocities suggest that the material is radially isotropic with $V_x$ almost equal to $V_y$, and $V_z$ less than $V_x$ and $V_y$. Up on increase of mean pressure, the material densifies and the velocities increase. However, at very large confining stress, the incremental change in the value of velocity in each direction is almost the same, indicating the material approaches the isotropic state. Further, an un-loading
Figure 4.3 Flow Chart of the Testing Procedure
Figure 4.4 Stress-Strain Plot for HC Test

1 psi = 6.89 kPa
Figure 4.5 Stress-Velocity Plot for HC Test

\[ 1\text{ psi} = 6.89 \text{ kPa} \]

Figure 4.6 Stress-Attenuation for HC Test
or decrease in confining pressure makes the material loose, with a decrease in the value of velocity. On loading and unloading to a same stress level, result in a different value of velocity, indicating that the material can not resume its original state. Thus, it can be concluded that the velocity of ultrasonic waves can be used to define and describe the anisotropy.

Figure (4.6) shows the variation of attenuation (A_x, A_y and A_z) with the confining pressure. At zero confining pressure, A_x > A_y > A_z, indicating that the material is initially anisotropic and the distribution of the micro-cracks in three directions are different due to sample preparation procedure. Upon increasing of confining pressure, the micro-cracks tend to close and the attenuations in three directions decrease. At very large confining pressures [90 psi (620 kPa)], the attenuations in three directions are identical, indicating the material has attained an isotropic state. However, a decrease in the value of the confining pressure would result in the widening of the micro-cracks and increase in the value of attenuation.

Figures (4.7) and (4.8) show the wave signatures at stress levels of 0 psi (0 kPa), 30 psi (207 kPa), 60 psi (414 kPa) and 90 psi (621 kPa), respectively along the virgin loading curve. It is observed in Figure (4.7) that the wave signatures in the X, Y and Z directions are different. The maximum amplitude of the waves used to compute attenuation is different in three directions, due to sample preparation. However, in Figure (4.8b) the value of the absolute maximum amplitudes in the three directions is almost the same, indicating an isotropic state. Transition from an initially anisotropic state to a (fully) isotropic state can be seen by observing the maximum amplitudes in the three directions in Figures (4.7) and (4.8). Also, an increase in the value of maximum amplitude with increase in confining pressure, reestablishes the fact that the material is being compacted and micro-cracks are being (fully) closed.

Based on the explanations given above it is evident that the sample is initially anisotropic and the magnitude of anisotropy decreases with the applied hydrostatic stress. Any definition leading to the quantification of induced anisotropy should consider this effect.
Figure 4.7 Wave Signatures along X, Y and Z directions for HC Test at Confining Pressures of (a) 0 psi (b) 30 psi (207 kPa)
Figure 4.8 Wave Signatures along X, Y and Z directions for HC Test at Confining Pressures of (a) 60 psi (414 kPa) (b) 90 psi (620 kPa)
4.3.2 CTC20 test

Figures (4.9) through (4.18) show the test results corresponding to CTC20 test. In this test, the sample is hydrostatically stressed up to 20 psi (138 kPa) and then sheared by increasing the stress $\sigma_z$, in the $Z$-direction. During the shear loading, the sample is subjected to two loading - unloading - re-loading cycles. At each stage of the test, ultrasonic response and mechanical response are recorded. Further, at pre-selected stress levels during shear phase, the sample is subjected to a hydrostatic stress of 1 psi (6.89 kPa) and then removed.

Figures (4.9) and (4.10) show the stress - strain and volumetric response of the sample. The stress strain data shown here, does not show the strains due to the hydrostatic (probe) stress, which will be used in Chapter 6. In these figures, $\tau_{oct}$ is the octahedral shear stress and $\varepsilon_v$ is the volumetric strain defined as

\[
\tau_{oct} = \frac{1}{3} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2} \quad (4.1)
\]
\[
\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z \quad (4.2)
\]

where $\sigma_x$, $\sigma_y$ and $\sigma_z$, $\varepsilon_x$, $\varepsilon_y$ and $\varepsilon_z$ are the stresses and strains in the three directions, respectively.

Figures (4.11) and (4.12) show the velocity and attenuation during the HC part of the test. It can be seen that the velocities and attenuations at any confining pressure, in the three directions are different, due to the initial anisotropy of the sample. An increase in velocity and decrease in attenuation with confining stress is observed. The material compacts and gradually looses its initial anisotropy.

Figures (4.13) through (4.16) show the wave signatures during the shear phase of the test at $\tau_{oct}$ of 0 psi [0 kPa, (beginning of the shear test)], 9.4 psi (65 kPa), 0 psi [0 kPa, (end of first unloading cycle)], 12.3 psi (85 kPa), 18.9 psi (130 kPa), 0 psi [0 kPa, (end of second unloading)], 20.3 psi (140 kPa) and 22.9 psi (158 kPa), respectively. Figure (4.13a) show the wave signatures along $X$, $Y$ and $Z$ directions at the beginning of shear phase. It is seen that the value of the absolute maximum amplitude in three directions are different although the sample was hydrostatically compacted up to this point.
Figure 4.9 Stress-Strain Response for CTC20 test $\sigma_0 = 20$ psi (138 kPa)

Figure 4.10 Volumetric Response for CTC20 test $\sigma_0 = 20$ psi (138 kPa)
Figure 4.11 Stress-Velocity Plot during HC part of CTC20 Test

Figure 4.12 Stress-Attenuation Plot during HC part of CTC20 Test
Figure 4.13 Wave Signatures along X, Y and Z directions for CTC20 test at $\tau_{ocf}$ of (a) 0 psi (b) 9.43 psi (65 kPa)
Figure (4.13b) shows the wave signatures during the shear phase of the test. There is a distinct change in the pattern of wave signatures at $\tau_{oct}$ of 9.43 psi (65 kPa) in three directions. Figure (4.14a) show the wave signatures at 0 psi (0 kPa) after the first un-loading cycle. The maximum amplitudes as compared with those in Figure (4.13a) are different. However, the wave signatures in X and Y directions (Figure 4.14a) are almost identical. Figure (4.15b) shows the wave signature at 0 psi (0 kPa) after the second unloading cycle. The maximum amplitude in X and Y directions decrease as compared with those at the end of first unloading cycle (Figure 4.14a). Figure (4.16b) show the wave signatures at $\tau_{oct}$ of 22.9 psi (158 kPa). It is seen that the wave signature in the X-direction has lost considerable amount of amplitude and the material is tending to fail. An important observation to be made here is that the wave signatures in the Z direction shows almost a constant amplitude, indicating that the increase of $\sigma_z$ has very little influence on densification in the Z direction.

The above variations in the form of wave signatures is essentially due to the stress path being followed in the test.

Figures (4.17) show the variation of ultrasonic velocities with the $\tau_{oct}$. The velocities in the X and Y directions decrease with an increase in shear stress, while, the velocity in the Z-direction increases initially and decreases after some value of $\tau_{oct}$. This is due to the fact that the material is under tension in the X and Y directions, while, it is under compression in the Z direction. At a value of $\tau_{oct}$ equal to 23 psi, the material dilates, there by a decrease in the value of $V_z$ is observed. Beyond this point, the $V_z$ decreases. However, $V_x$ and $V_y$ were not possible to record using the pulser / receiver unit, as the waves scatter because of the presence of large number of (expanding) micro-cracks. Figures(4.18) show the variation of attenuations in the three directions with the shear stress, in the X, Y and Z directions. It can be seen that the values of $A_x$ and $A_y$ decrease with $\tau_{oct}$ up to the point of dilation (very close to 23 psi) and then increase with $\tau_{oct}$. While, $A_z$ remains unchanged. Further, it is observed that at very large $\tau_{oct}$ very close to failure, $A_x$, $A_y$ and $A_z$ increase because of the presence of micro-cracks. The reason for no change in $A_z$ with $\tau_{oct}$ is given below. Initially, the material was anisotropic with a lot of micro-cracks in it.
Figure 4.14 Wave Signatures along X,Y and Z directions for CTC20 test at $\tau_{ocf}$ of (a) 0 psi (after first unloading) (b) 12.25 psi (84.4 kPa)
Figure 4.15 Wave Signatures along X, Y and Z directions for CTC20 test at $\tau_{oct}$ of (a) 18.9 psi (130 kPa) (b) 0 psi (after second unloading cycle)
Figure 4.16 Wave Signatures along X, Y and Z directions for CTC20 test at \( r_{ocf} \) of (a) 20.3 psi (140 kPa) (b) 22.9 psi (158 kPa)
Figure 4.17 Variation of Velocity with $\tau_{oct}$ for CTC20 test
Figure 4.18 Variation of Attenuation with $\tau_{oct}$ for CTC20 test
Application of confining pressure up to 20 psi (138 kPa), makes these cracks close. When these cracks close, the attenuation of the signal will be lower. There is a threshold limit, beyond which, the application of additional compressive stresses have almost no influence on the attenuation values. However, unloading below this limit results in an increase in the value of the attenuation, as the cracks tend to open. Finally, it is observed that the attenuation values at failure are almost the same in three directions.

Based on the explanations given above it is concluded that the velocity and attenuation can be used to quantify induced anisotropy even during the shear tests.

4.3.3 CTC30 test

Figures (4.19) through (4.27) show the test results corresponding to CTC30 test. In this test, the sample is hydrostatically stressed up to 30 psi (207 kPa) and then sheared by increasing the stress $\sigma_z$ in the Z-direction. During the shear loading, the sample is subjected to two loading - unloading - reloading cycles. At each stage of the test, ultrasonic response and mechanical response are recorded. Further, at pre-selected stress levels during shear phase, the sample is subjected to a hydrostatic stress of 1 psi (6.89 kPa) and then removed. Figures (4.19) and (4.20) show the stress-strain and volumetric response of the sample, respectively.

Figures (4.21) and (4.22) show the velocity and attenuation during the HC part of the test. It can be seen that the velocities and attenuations at any confining pressure, in the three directions are different. This is attributed to the initial anisotropy in the sample. During HC part of the test, the velocities in three directions increase, while the attenuations decreases.

Figures (4.23) through (4.25) show the wave signatures during the shear phase of the test at $\tau_{oct}$ of 0 psi [0 kPa, (beginning of the shear test)], 5.6 psi (39 kPa), 9.9 psi (68 kPa), 0 psi [0 kPa, (end of first unloading cycle)], 19.8 psi (136 kPa) and 22.5 psi (155 kPa), respectively. It is observed that the wave signatures in three directions are different at different values of shear stress. Figure (4.23a) shows the wave signatures at the beginning of the shear part of the CTC30 test.
Figure 4.19 Stress-Strain Response for CTC30 test with $\sigma_0 = 30$ psi (206.7 kPa)

Figure 4.20 Volumetric Response for CTC30 test with $\sigma_0 = 30$ psi (206.7 kPa)
Figure 4.21 Stress-Velocity Plot during HC part of CTC30 test

\[ 1 \text{psi} = 6.89 \text{ kPa} \]

Figure 4.22 Stress-Attenuation Plot during HC part of CTC30 test
Figure 4.23 Wave Signatures along X, Y and Z directions for CTC30 test at 

\( \tau_{ocf} \) of (a) 0 psi (b) 5.6 psi (38.6 kPa)
Figure 4.24 Wave Signatures along X, Y and Z directions for CTC30 test at \( \tau_{ocf} \) of (a) 9.9 psi (68.2 kPa) (b) 0 psi (after first unloading)
Figure 4.25 Wave Signatures along X, Y and Z directions for CTC30 test at \( \tau_{oc} \) of (a) 19.8 psi (136.4 kPa) (b) 22.5 psi (155 kPa)
It is seen that the amplitude in X and Y directions are the same while that in the Z direction is different. Up on increasing $\tau_{oct}$ to 5.6 psi \((39\text{ kPa})\), Figure (4.23b)], the amplitude in the Z direction increases, while that in X and Y direction decrease. This is due to the fact that the material is being densified in the Z direction. On further loading to 9.9 psi \((68\text{ kPa})\) and unloading to 0 psi \([0\text{ kPa}, \text{ Figure (4.24b)}]\), a decrease in the value of maximum amplitude in the X, Y and Z direction, as compared to those at the beginning of the test \((\text{Figure 4.23a})\). Finally, on increasing the $\tau_{oct}$ to a large value a decrease in the values of amplitudes in the X and Y directions, while an increase in the value of the amplitude is observed in the Z direction.

Figure (4.26) show the variation of velocity with $\tau_{oct}$. Here, $V_x$ and $V_y$ decrease with $\tau_{oct}$, while $V_z$ increases with $\tau_{oct}$. This is due to the fact that the material expands (loosens) in the X and Y directions, while it compresses (densifies) in the Z direction. However, at a very large value of $\tau_{oct}$ $V_z$ stabilizes to a constant value.

Figure (4.27) show the variation of attenuation with $\tau_{oct}$. It is seen that $A_x$ and $A_y$ increase with $\tau_{oct}$, while $A_z$ decreases. A decrease in $A_x$ and $A_y$ is due to the widening of micro-cracks and increase in $A_z$ is due to densification. This observation is consistent with the mode of deformation, occurring within the material.

4.3.4 TE45 test

Figures (4.28) through (4.35) show the test results for TE45 test. In this test, the sample is subjected to stresses along HC path up to 45 psi \((310\text{ kPa})\) and then sheared. During the shear test, the value of $\sigma_z$ is decreased while $\sigma_x$ and $\sigma_y$ are increased so that the mean pressure remains constant. Figures (4.28) and (4.29) show the stress-strain and volumetric response for this test, respectively. Figures (4.30) and (4.31) show the variation of velocity and attenuations along three directions during the HC part of the test. It is seen that at the beginning of the test, the velocities and attenuations in the three directions are different. On increasing the value of confinement to 45 psi \((310\text{ kPa})\), the velocities in three directions attain
Figure 4.26 Variation of Velocity with $\tau_{oct}$ for CTC30 test

$1\text{psi} = 6.89\text{ kPa}$
Figure 4.27 Variation of Attenuation with $\tau_{oct}$ for CTC30 test

$1\text{psi} = 6.89\text{kPa}$
Figure 4.28 Stress-Strain Response for TE45 test with \( \sigma_0 = 45 \) psi (310 kPa)

Figure 4.29 Volumetric Response for TE45 test with \( \sigma_0 = 45 \) psi (310 kPa)
Figure 4.30 Stress-Velocity Plot during HC part of TE45 test

Figure 4.31 Stress-Attenuation Plot during HC part of TE45 test
Figure 4.32 Wave Signatures along X, Y and Z directions for TE45 Test at 
\(\tau_{\text{ocf}}\) of (a) 0 psi (b) 4.24 psi (29.2 kPa)
Figure 4.33 Wave Signatures along X, Y and Z directions for TE45 Test at $\tau_{ec}$ of (a) 14.1 psi (97.2 kPa) (b) 19 psi (131 kPa)
a constant value, while the attenuations in X and Y directions are the same, with that in the Z direction different.

Figures (4.32) and (4.33) show the wave signatures along X, Y and Z directions at $\tau_{oct}$ of 0 psi (0 kPa), 4.24 psi (29 kPa), 14.1 psi (97 kPa) and 19 psi (131 kPa), respectively. It is observed that there is a change in the pattern of these waves. Figure (4.23a) show the wave signatures at the beginning of the shear phase. The maximum amplitude in the three directions are different and also the wave pattern. On increasing $\tau_{oct}$ to 4.2 psi (29 kPa), amplitude in the Z direction decreases, while that in the X and Y directions increase. The wave signature at 19 psi correspond to the stress close to failure. At this point, the material has almost failed and the ultrasonic energy is lost in passing through the specimen.

Figure (4.34) show the variation of velocity $V_x$, $V_y$ and $V_z$ with $\tau_{oct}$. Here, $V_x$ and $V_y$ remain almost constant, while $V_z$ decreases up on increase in $\tau_{oct}$. This behavior of constant $V_x$ and $V_y$ is due to the fact that the densification has reached its critical point in the X and Y directions. A decrease in $V_z$ is due to the expansion of micro-cracks in the Z direction. Figure (4.35) show the variation of attenuation with $\tau_{oct}$. It is seen that $A_x$ and $A_y$ remain almost constant, while $A_z$ increases initially and then starts to decrease. The latter behavior can be explained as follows. Initially has three (artificial) layers normal to Z direction, due to sample preparation. During the initial part of the extension test these layers tend to widen with increase in $\tau_{oct}$. But at very large $\tau_{oct}$, interaction of these layers might result in their closure, thereby decreasing the attenuation.

Based on the explanations given above it can be concluded that the ultrasonic velocity and attenuation indeed describe the internal changes occurring during extension also.

4.3.5 TC30 test

Figures (4.36) through (4.44) show the test results for the TC30 test. In this test, the specimen is stressed to a mean pressure of 30 psi (207 kPa) and then sheared along the Z-direction. During the shear phase of the test, $\sigma_z$ is increased, while $\sigma_x$ and $\sigma_y$ are decreased so that the mean pressure is held constant at 30 psi
Figure 4.34 Variation of Velocity with $\tau_{oct}$ for TE45 test

Figure 4.35 Variation of Attenuation with $\tau_{oct}$ for TE45 test
Figure 4.36 Stress-Strain Response for TC30 test with $\sigma_0 = 30$ psi (206.7 kPa)

Figure 4.37 Volumetric Response for TC30 test with $\sigma_0 = 30$ psi (206.7 kPa)
(207 kPa). Figures (4.36) and (4.37) show the stress-strain and volumetric response for this test, respectively. In Figure (4.37) there is a sudden increase in the value of volumetric strain at the point of dilation. This behavior is due to the application of a large stress increment during the test.

Figures (4.38) and (4.39) show the variation of velocities and attenuations in the three directions during the HC part of the TC30 test. The velocity increases with the confining pressure, while, the attenuation decreases. Figures (4.40) through (4.42) correspond to the wave signatures during the shear phase of the test, at $\tau_{oct}$ of 0 psi (0 kPa), 3.0 psi (20.4 kPa), 0 psi [0 kPa, (after the first unloading)], 6 psi (42 kPa), 10 psi (69 kPa) and 13 psi (90 kPa), respectively. The amplitude of wave signatures in X and Y directions at the beginning of the test (Figure 4.40a) is higher than that at $\tau_{oct}$ of 13 psi (90 kPa) (Figure 4.42b). While, the converse is true for the Z direction. Figures (4.43) and (4.44) show the variation of velocity and attenuations during the shear part of the test. It is seen that $V_x$ and $V_y$ decrease with $\tau_{oct}$, while $V_z$ increases. Attenuations $A_x$ and $A_y$ decrease, while $A_z$ remains constant with $\tau_{oct}$. However, at failure $A_x$, $A_y$ and $A_z$ reach the same value.

4.3.6 TE30 test

Figures (4.45) through (4.52) show the test results for the TE30 test. In this test, the specimen is stressed to a mean pressure of 30 psi (207 kPa) and then sheared along the extension path in the Z-direction. During the shear phase of the test, the mean pressure is held constant at 30 psi (207 kPa). Figures (4.45) and (4.46) show the stress-strain and volumetric response for this test, respectively. The stress-strain curve at the ultimate value of stress shows a sudden break due to the brittle nature of the material and also due to a large stress increment close to failure.

Figures (4.47) and (4.48) show the variation of velocities and attenuations in the three directions during the HC part of the TE30 test. The velocity increases with the confining pressure, while, the attenuation decreases. Figures (4.49) through (4.50) correspond to the wave signatures during the shear phase of the test, at $\tau_{oct}$ of 0 psi, 3 psi (21 kPa), 6 psi (42 kPa) and 10 psi (69 kPa), respectively. Figures
Figure 4.38 Stress-Velocity Plot during HC part of TC30 test

Figure 4.39 Stress-Attenuation Plot during HC part of TC30 test
Figure 4.40 Wave Signatures along X, Y and Z directions for TC30 Test at $\tau_{ocf}$ of (a) 0 psi (b) 3 psi (20.4 kPa)
Figure 4.41 Wave Signatures along X, Y and Z directions for TC30 Test at $\tau_{ocf}$ of (a) 0 psi (after first unloading) (b) 6 psi (42 kPa)
Figure 4.42 Wave Signatures along X, Y and Z directions for TC30 Test at $\tau_{oct}$ of (a) 10 psi (69 kPa) (b) 13 psi (90 kPa)
Figure 4.43 Variation of Velocity with $\tau_{oct}$ for TC30 test

Figure 4.44 Variation of Attenuation with $\tau_{oct}$ for TC30 test
Figure 4.45 Stress-Strain Response for TE30 test with $\sigma_0 = 30$ psi (207 kPa)

Figure 4.46 Volumetric Response for TE30 test with $\sigma_0 = 30$ psi (207 kPa)
Figure 4.47 Stress-Velocity Plot during HC part of TE30 test

Figure 4.48 Stress-Attenuation Plot during HC part of TE30 test
Figure 4.49 Wave Signatures along X, Y and Z directions for TE30 Test at $\tau_{oct}$ of (a) 0 psi (b) 3 psi (21 kPa)
Figure 4.50 Wave Signatures along X, Y and Z directions for TE30 Test at $\tau_{oct}$ of (a) 6 psi (42 kPa) (b) 10 psi (69 kPa)
Figure 4.51 Variation of Velocity with $\tau_{oct}$ for TE30 test

Figure 4.52 Variation of Attenuation with $\tau_{oct}$ for TE30 test
(4.51) and (4.52) show the variation of velocity and attenuations during the shear part of the test, respectively.

4.3.7 CTC10 test

Figures (4.53) through (4.59) show the test results for the CTC10 test. In this test, the specimen is stressed to a mean pressure of 10 psi (69 kPa) and then sheared along the compression path in the Z-direction. Figures (4.53) and (4.54) show the stress-strain and volumetric response for this test, respectively. In this test also, at the ultimate state there is a brittle failure in the material.

Figures (4.55) through (4.57) correspond to the wave signatures during the shear phase of the test, at $\tau_{oc}$ of 0 psi, 4.9 psi (34 kPa), 0 psi (0 kPa, after the first unloading cycle), 9.8 psi (67.5 kPa), 0 psi (0 kPa, after the second unloading cycle) and 16.3 psi (112 kPa), respectively. Figures (4.58) and (4.59) show the variation of velocity and attenuations during the shear part of the test, respectively.

4.4 Summary of Test Results

Based on the explanations given in the previous sections, the following important conclusions can be drawn for the ultrasonic response:

1. the wave signatures give a physical (visual) evidence of internal changes occurring within the material due to the application of external stresses.

2. the velocity of the ultrasonic wave increases with the increase in confining pressure.

3. the velocity increases with compressive stress and decrease with the tensile stress.

4. the velocity decreases with unloading and increases with re-loading. Variation of velocity with loading and unloading in any given particular sequence is not the same.
Figure 4.53 Stress-Strain Response for CTC10 test with $\sigma_0 = 10$ psi (69 kPa)

Figure 4.54 Volumetric Response for CTC10 test with $\sigma_0 = 10$ psi (69 kPa)
Figure 4.55 Wave Signatures along X, Y and Z directions for CTC10 Test at $	au_{oct}$ of (a) 0 psi (b) 4.9 psi (34 kPa)
Figure 4.56 Wave Signatures along X, Y and Z directions for CTC10 Test at \( \tau_{oct} \) of (a) 0 psi (after first unloading cycle) (b) 9.8 psi (68 kPa)
Figure 4.57 Wave Signatures along X, Y and Z directions for CTC10 Test at $\tau_{oc}$ of (a) 0 psi (after second unloading cycle) (b) 16.3 psi (112 kPa)
Figure 4.58 Variation of Velocity with $\tau_{oct}$ for CTC10 test

1 psi = 6.89 kPa
Figure 4.59 Variation of Attenuation with $\tau_{oc}$ for CTC10 test

1 psi = 6.89 kPa
5. The attenuation decreases with confining pressure and reaches a constant value at a very large confining pressure. The value of this (constant or threshold) attenuation remains to be same in all three directions for any given test.

6. The attenuation decreases with the compressive stresses and increases with the tensile stresses. However, if the sample has experienced a saturation state (as explained in 4.), the addition of compressive stresses has no significant change in the value of attenuation.

7. The attenuation increases with unloading and decreases with reloading. In most of the cases, unloading and reloading sequence results in different values of attenuation.

8. The ultrasonic velocity and attenuation indeed describe the internal changes occurring in the material, and represent a physical measure of those changes.
CHAPTER 5

DETERMINATION OF PARAMETERS AND VERIFICATION OF THE MODEL

5.1 General

In this chapter, procedures for determining material parameters for the $\delta_1$ model are presented. This is followed by the verification of the model by back prediction.

5.2 Determination of Material Parameters for $\delta_1$ Model

For the $\delta_1$ model the material constants are found based on four different states of a material deformation process: the elastic, plastic accompanied by hardening, phase change from compaction to dilation and the ultimate state. In addition, a non-associative parameter is required. Thus, the constants to be evaluated are:

1. elastic constants: $E$ and $\nu$
2. ultimate parameters: $\gamma, \beta, m$
3. phase change parameter: $n$
4. constants related to the hardening process: $a_1, \eta_1$ and $\kappa$

For evaluating these material constants, standard procedures are available (Desai et al. 1986, Desai and Wathugala 1987). In this dissertation the procedure to determine the constants is explained very briefly. Further, in the current research, the ultimate constants are determined by using all the tests described in Chapter 3, while, phase change parameter, hardening parameters and non-associative parameters are determined using CTC20, CTC30 and TE45 tests.

5.2.1 Elastic constants, $E$ and $\nu$

In the case of an isotropic material, a minimum of two elastic constants are needed to describe the elastic behavior. The two most commonly used elastic constants, are the Young’s modulus, $E$, and the Poisson’s ratio $\nu$. These elastic
constants are obtained by using the unloading - reloading slopes of the shear tests. To consider the effect of all stress paths into the determination of elastic constants, it is better to find the values from each stress paths and then adopt a weighted average value. Depending on the need, it may also be possible to express $E$ as a function of the confining pressure. The average values of elastic constants for the cemented sand, under consideration are:

$E = 17515 \text{ psi (1.2x10}^5 \text{ kPa)} \text{ and } \nu = .353$

**Elastic constants using ultrasonic velocity:**

For an isotropic material, the elastic constants are related to the ultrasonic velocity and mass density $\rho$ by the relation,

$$
\bar{V}^2 = \frac{E_d (1 - \nu_d)}{\rho (1 + \nu_d) (1 - 2\nu_d)} \quad (5.1)
$$

Where, $\bar{V} = (V_x + V_y + V_z)/3$ is the average P-wave velocity for the material, $E_d$ is the dynamic Young's modulus and $\nu_d$ is the dynamic Poisson's ratio. By assuming $\nu_d = \nu = 0.353$ and for known values of $\bar{V}$ and $\rho$ we can compute $E_d$ using Equation (5.1).

Table (5.1) shows the summary of results for a number of tests. It is observed from this Table that the Young's modulus, $E$ (obtained by using the un-loading slopes of the stress strain curves) and the dynamic Young's modulus, $E_d$ (computed by using Equation (5.1)) are comparable. A linear least square fit between the two measures gives an expression:

$$
E = 0.15 \ E_d \quad (5.2)
$$

This expression can be used to estimate the Young's modulus, $E$, for the known value of $E_d$ for cemented sand.
Table 5.1 Elastic Parameters Based on Ultrasonic Velocity

<table>
<thead>
<tr>
<th>TEST</th>
<th>Density</th>
<th>P-Wave Velocity</th>
<th>Dynamic Young's Modulus</th>
<th>Young's Modulus **</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pcf (kN/m^3)</td>
<td>ft/sec (m/sec)</td>
<td>psi (kPa) x 10^3</td>
<td>psi (kPa) x 10^3</td>
</tr>
<tr>
<td>CTC20</td>
<td>119 (18.71)</td>
<td>2933 (894)</td>
<td>135.7 (935)</td>
<td>17.05 (117)</td>
</tr>
<tr>
<td>CTC30</td>
<td>113 (17.76)</td>
<td>2233 (681)</td>
<td>74.5 (514)</td>
<td>17.40 (120)</td>
</tr>
<tr>
<td>TE45</td>
<td>114 (17.92)</td>
<td>2533 (772)</td>
<td>97.0 (667)</td>
<td>--</td>
</tr>
<tr>
<td>TC30</td>
<td>112 (17.61)</td>
<td>2892 (881)</td>
<td>124.2 (855)</td>
<td>18.95 (130)</td>
</tr>
<tr>
<td>TE30</td>
<td>119 (18.71)</td>
<td>2600 (792)</td>
<td>106.8 (735)</td>
<td>17.38 (120)</td>
</tr>
</tbody>
</table>

Note:

** = Based on un-loading slopes
-- = Not available
5.2.2 Ultimate parameters $\gamma, \beta$ and $m$

The parameters $\gamma$ and $\beta$ are obtained by considering the ultimate stress state. While, $m$ has a value of $-0.5$, based on laboratory tests on a number of geological materials (sand, clay, rock and concrete) (Desai et al. 1986).

Figure (5.1) show the plot of $\sqrt{J_{2D}}$ versus $J_1$ at ultimate for a number of stress paths, explained in Chapter 4. An expression for ultimate state in terms of $\sqrt{J_{2D}}$, $J_1$ and ultimate parameters can be written as (Desai and Wathugala, 1987):

$$\frac{\Delta \sqrt{J_{2D}}}{\Delta J_1} = \sqrt{\gamma (1 - \beta S_r)^m} \quad (5.3)$$

where, $S_r$ is stress ratio and has a value of 1, -1 and 0, for compression, tension and simple shear stress paths, respectively. $\Delta \sqrt{J_{2D}}$ and $\Delta J_1$ are the incremental values of $\sqrt{J_{2D}}$ and $J_1$, respectively. By knowing the slopes of two ultimate envelopes (Figure (5.1)), the parameters $\gamma$ and $\beta$ are determined. The two ultimate envelopes meet the $J_1$ axis at a value of $J_1$ equal to 100 psi (689 kPa). The values of ultimate parameters for cemented sand are:

$\gamma=0.01337$; $\beta=0.6369$ and $m=-0.5$

5.2.3 Phase change parameter, $n$

The value of $n$ is found by considering the stress state at the zero volume change. An expression for $n$ in terms of ultimate parameters can be written as (Desai and Wathugala (1987)),

$$n = \frac{2}{\left(1 - \frac{J_{2D}/J_1^2}{\gamma(1 - \beta S_r)^m}\right)} \quad (5.4)$$

An average value of $n=8.64$ has been obtained for the cemented material.

5.2.4 Hardening parameters, $a_1, \eta_1$

The relation between the hardening function $\alpha$ and the trajectory of the plastic strain, $\zeta$ is given by:

$$\alpha = \frac{a_1}{\zeta_1} \quad (5.5)$$
Figure 5.1 Determination of Ultimate Parameters
From each test, \( \alpha \) values are found for several points using the condition, \( F=0 \), as all other parameters are known. The corresponding \( \zeta \) can be found from the plastic strain trajectory up to the specific strain level corresponding to the stress level under consideration. Then a plot of \( \alpha \) versus \( \zeta \) on a logarithmic scale and using the least square fit, the hardening parameters \( a_1 \) and \( \eta_1 \) are computed.

In the present study, CTC20, CTC30 and TE45 tests are used to determine the hardening parameters. Figure (5.2) shows a plot of \( \alpha \) versus \( \eta \) on a logarithmic scale. A best fit line drawn through these points gives the value of \( a_1 \) and \( \eta_1 \). The values of hardening parameters are:

\[
\begin{align*}
a_1 &= 0.266 \times 10^{-11} \quad \text{and} \quad \eta_1 = 0.566
\end{align*}
\]

5.2.5 Non-associative parameter, \( \kappa \)

The non-associative parameter, \( \kappa \) is computed using the volumetric response of the material under various stress paths, at the ultimate condition (Hashmi (1986)). An expression for \( \kappa \) is given by:

\[
\kappa = \frac{(\alpha_Q - \alpha)}{(\alpha_0 - \alpha)(1 - r_v)}
\]

(5.6)

Where, \( r_v = \zeta_a / \zeta \) and \( \alpha_0 \) is the value of \( \alpha \) at the beginning of shear phase. The average value of \( \kappa \) is found to be equal to 0.0025 for the cemented material.

5.3 Verification of the Model

A reliable constitutive model should be able to back predict the laboratory test used in evaluating its material constants. In the last section the constants were determined by using CTC20, CTC30 and TE45 tests. In this section the experimental tests are verified by back predicting them.

5.3.1 Back prediction of test results

The back prediction of the stress-strain response is obtained by integrating the incremental stress-strain relation

\[
\sigma_{ij} = C_{ijkl}^{cp} \, d\epsilon_{kl}
\]

(5.7)
Figure 5.2 Determination of Hardening Parameters
or its inverse relation

\[ d\varepsilon_{ij} = D_{ijkl}^{ep} \, d\sigma_{ij} \]  \hspace{1cm} (5.8)

Where \( d\sigma_{ij} \) and \( d\varepsilon_{ij} \) are the incremental stress and strain vectors, respectively, \( C_{ijkl}^{ep} \) is the elasto-plastic constitutive matrix and \( D_{ijkl}^{ep} \) is the elasto-plastic compliance matrix. As the tests performed are stress-controlled, Equation (5.8) is used for the back prediction.

If the incremental quantities are small, the integration of Equation (5.8) at the end of \( m \)th increment can be expressed as

\[ \varepsilon_{ij}^{(m)} = \varepsilon_{ij}^{(0)} + \sum_{n=1}^{n=m} D_{ijkl}^{ep} \, (n-1) \, d\sigma_{kl} \]  \hspace{1cm} (5.9)

where \( \varepsilon_{ij}^{(0)} \) is the initial strain vector and \( \varepsilon_{ij}^{(m)} \) is the strain vector at the end of \( m \)th increment and \( m \) varies between \( n \) and total number of increments.

Use of the above equations require very small increments. This can involve considerable computational efforts and can lead to costly calculations. If the increments are not very small, the stress state at the end of the increment may not lie on the current yield surface leading to the problem of the drift of the yield surface. A back prediction program written by Desai and Sharma (1989) has been used for the back prediction of CTC20, CTC30 and TE45 tests, using the parameters determined in the previous section.

Figures (5.3) through (5.8) show the back predictions along with the test data for CTC20, CTC30 and TE45 tests. It can be seen that the stress-strain response is fairly accurately predicted by the model for all the tests. However the volumetric response is predicted very well by the model for the CTC30 test (Figure 5.6). In the present investigation, the average parameters obtained in the previous section will be used to obtain mechanical anisotropy as predicted by the \( \delta_1 \) model.
Figure 5.3 Back Prediction of CTC20 Test using $\delta_1$ Model

Figure 5.4 Back Prediction of CTC20 Test
Figure 5.5 Back Prediction of CTC30 Test

Figure 5.6 Back Prediction of CTC30 Test
Figure 5.7 Back Prediction of TE45 Test

Figure 5.8 Back Prediction of TE45 Test
CHAPTER 6

MECHANICAL AND ULTRASONIC ANISOTROPY

6.1 General

The main objective of this dissertation is to study the stress induced material anisotropy of cemented sand. As mentioned in Chapter 3, we identify two measures of anisotropy, namely, mechanical and ultrasonic anisotropy. The mechanical anisotropy is a function of strains developed within the material due to the application of stress. While, the ultrasonic anisotropy is a physical measure, related to the variations in the values of attenuation and velocity due to the applied stress.

6.2 Mechanical Anisotropy

The mechanical anisotropy is computed based on the available constitutive laws. It has been established (Desai, Somasundaram, and Frantziskonis, 1986), that the non-associativeness or deviation from normality could describe the induced anisotropy within the material. Therefore in this study, the model is used to compute the strains, which can be used to define and quantify the induced anisotropy.

Consider an element of the material (Figure (6.1)) which is undergoing a sequence of loading and unloading (could be either hydrostatic or shear). At any given state, let \( \sigma_i \) and \( \epsilon_i \) \((i = X, Y, Z)\) be the stress and strain in three directions, respectively. We assume that the material is subjected to a very small hydrostatic stress increment, \( \delta \sigma \). Let \( \Delta \epsilon \) be the strain in three directions, due to this increment of hydrostatic stress. The material is said to be isotropic if the incremental strains in three directions are same. If the material is anisotropic, the incremental strain values in three directions will be different. Let \( \bar{\epsilon} \) be the average incremental strain in the material. Then, the ratio \( \Delta \epsilon_i / \bar{\epsilon} \) gives a measure of anisotropy in the \( i \)th direction. Since we need an over-all measure of mechanical anisotropy at any given state, we can define \( M_{\text{anis}} \) as:
Figure 6.1 Definition of Mechanical Anisotropy
In order to quantify the mechanical anisotropy, a set of special tests have to be performed. In these special tests, a small hydrostatic stress is applied at pre-selected points of stress paths and the incremental strains in the three directions are recorded. The applied hydrostatic stress is removed and the stress path is continued. The mechanical anisotropy is then computed using Equation (6.1). However, since it is difficult to perform such tests along a number of stress paths, an indirect method has been suggested. In this method, special tests are simulated using the \( \delta_1 \) model defined by the material constants found in Chapter 5. In these special tests, following procedure is adopted. At any stress state, the elasto-plastic matrix, \( C_{ijkl}^{ep} \), is computed using the constitutive constants given in Chapter 5. A uniform hydrostatic stress increment of 1 psi (6.89 kPa) is applied and the incremental strains in the three directions are found using the equation (5.6). The material is isotropic if the computed incremental strains in the three directions are the same. If the material is anisotropic the degree of mechanical anisotropy is computed using Equation (6.1). In order to simulate (predict) such tests, a computer program written by Desai and Sharma (1989) has been modified and used. The validity of such an approach has to be checked with the available experimental results. In the present investigation, as mentioned in Chapter 3, two special tests (CTC20 and CTC30) have been performed. Herein, the mechanical anisotropy as obtained by the experiment is compared with the predicted anisotropy, as computed by the program.

Figures (6.2) and (6.3) compares the mechanical anisotropies obtained by the model and the experimentally obtained anisotropy for the CTC20 and CTC30 tests, respectively. Here, \( M_{anis} \) has been obtained by the \( \delta_1 \) model along the virgin part of the stress-strain curve and includes the contribution due to the initial anisotropy of the material. Following points are observed from these figures.
Figure 6.2 Variation of Mechanical Anisotropy for CTC20 Test
Figure 6.3 Variation of Mechanical Anisotropy for CTC30 Test
1. Along the virgin curve, $M_{\text{anis}}$ as computed by the $\delta_1$ model show similar trend as that obtained experimentally.

2. Along the virgin curve, $M_{\text{anis}}$ increases with $\tau_{\text{oct}}$, reaches a peak value, suddenly decreases and tends towards a stable (constant value). The point at which $M_{\text{anis}}$ is maximum depends on the type of stress path followed and it corresponds to a point very close to the point of dilation. This phenomenon will be explained later.

3. $M_{\text{anis}}$ at zero $\tau_{\text{oct}}$ as predicted by the model is not defined as the strains are assumed to be zero at the beginning of shear.

4. Experimental $M_{\text{anis}}$ values increase up on loading and unloading to a zero value of $\tau_{\text{oct}}$. This implies that the material can not retain its previous value of $M_{\text{anis}}$ in going through a cycle of loading and unloading.

The phenomenon in 2 can be explained as follows: At the start of the shear test, the material is initially anisotropic due to the preffered orientation of the particles. Up on increasing the shear stress, these particles attain a new orientation. This preferred orientation of particles gives an unequal incremental strains in the three directions, due to the application of a very small hydrostatic stress increment. This process continues until the peak point is reached. Beyond this point, the material dilates (loosens) and the particles re-orient to a configuration as before, which results in the decrease in value of $M_{\text{anis}}$. Finally, at a large value of shear stress (close to ultimate), there will be considerable amount of particle (grain) crushing that the preffered orientation is completely destroyed. Therefore, the $M_{\text{anis}}$ attains a stable value.
6.3 Ultrasonic Anisotropy

The ultrasonic anisotropy is a physical measure of the anisotropy and is quantified based on the experimentally available velocities and attenuations. In the case of ultrasonic anisotropy, we define two forms: velocity anisotropy and attenuation anisotropy.

Consider an element of the material (Figure (6.1)) which is undergoing a sequence of loading and unloading (could be either hydrostatic or shear). At any given state, let \( V_i \) and \( A_i \) \((i = X, Y, \text{and} \ Z)\) be the velocity and attenuation in three directions, respectively. The material is said to be isotropic if the velocity and attenuation in the three directions are same. If the material is anisotropic, the velocity and attenuation values in three directions will be different. Let \( \bar{V} \) and \( \bar{A}_i \) be the average velocity and attenuation in the material, respectively. Then, the ratio \( V_i / \bar{V} \) and \( A_i / \bar{A} \) gives a measure of ultrasonic anisotropy in the \( i \)th direction at any given state of the material. Since we need an over-all measure of ultrasonic anisotropy at any given state, we can define the velocity anisotropy \( (V_{anis}) \) and the attenuation anisotropy \( (A_{anis}) \) as follows.

\[
V_{anis} = \sqrt{\sum_{i=1}^{3} (1 - V_i / \bar{V})^2}
\]

(6.2)

\[
A_{anis} = \sqrt{\sum_{i=1}^{3} (1 - A_i / \bar{A})^2}
\]

(6.3)

6.4 Comparison of Mechanical and Ultrasonic Anisotropy

Figure (6.4) show the variation of \( M_{anis} \) with the applied confining pressure \( (\sigma_0) \) for the HC mtest. The figure also show the test results during the hydrostatic compression phase of CTC20, CTC30, TE45, TC30 and TE30 tests. In this figure, the scatter of \( M_{anis} \) values at zero (low) confining pressure indicate the presence of initial anisotropy in all the samples. These values decrease asymptotically with increase in mean pressure, which is typical of geologic materials. Further at low \( \sigma_0 \), \( M_{anis} \) initially increase and then decrease with increase in \( \sigma_0 \). This behavior
Figure 6.4 Variation of Mechanical Anisotropy for HC Tests

1 psi = 6.89 kPa
is due to the initial shear strains (due to the sample preparation procedure) in the material.

Figure (6.5) show the variation of $V_{\text{anis}}$ with the applied confining pressure ($\sigma_0$), for the HC test. The figure also show the test results during the hydrostatic compression phase of CTC20, CTC30, TE45, TC30 and TE30 tests. In this figure, the scatter of $V_{\text{anis}}$ values at zero (low) confining pressure indicate the presence of initial velocity anisotropy in all the samples. These values decrease asymptotically with increase in mean pressure. Here also at low $\sigma_0$, $V_{\text{anis}}$ initially increase and then decrease with increase in $\sigma_0$.

Figure (6.6) show the variation of $A_{\text{anis}}$ with the applied confining pressure ($\sigma_0$), for the same tests during the hydrostatic compression phase of the tests. In this figure, the scatter of $A_{\text{anis}}$ values at zero (low) confining pressure indicate the presence of initial attenuation anisotropy in all the samples. These values decrease asymptotically with increase in mean pressure.

Figure (6.7) shows the variation of $V_{\text{anis}}$ and $A_{\text{anis}}$ for the HC test including the effects of loading and unloading. It is observed that the value of ultrasonic anisotropy is affected significantly by the loading and unloading procedure. Therefore, it can be concluded that the three measures of anisotropies show similar trends and provide a guideline for the development of suitable correlation functions between them.

Figure (6.8) show a comparison of $M_{\text{anis}}$, $V_{\text{anis}}$ and $A_{\text{anis}}$ for the CTC20 test. In this figure $M_{\text{anis}}$ is computed using Equation (6.1) based on the values of strains obtained from the program, and Equation (6.1). While, the values of $V_{\text{anis}}$ and $A_{\text{anis}}$ are computed using the Equation (6.2) and (6.3), respectively. The values of $V_i$ and $A_i$ to be used in these expressions are based on the experimental values of the CTC20 test, described in Chapter 4. In this figure the value of $V_{\text{anis}}$ has been shown only up to a value of $\tau_{\text{oct}}$ equal to 23 psi (160 kPa), because, the pulser / receiver unit failed to read out the velocity values beyond this point during the experiment. It is to be noted here that $M_{\text{anis}}$ and $A_{\text{anis}}$ show similar trends over the entire range of $\tau_{\text{oct}}$. 
Figure 6.5 Variation of Velocity Anisotropy for HC Tests

1 psi = 6.89 kPa
Figure 6.6 Variation of Attenuation Anisotropy for HC Tests

1psi = 6.89 kPa
Figure 6.7 Variation of Ultrasonic Anisotropy during loading and unloading for HC Test.
Figure 6.8 Variation of Mechanical and Ultrasonic Anisotropy for CTC20 Test
It is observed from Figure (6.8) that $M_{anis}$ increases with $\tau_{oct}$, attains a maximum value and then decreases. This behavior is due to the interaction of shear and the hydrostatic deformations occurring in the material, along the CTC path. During the test, increase in the mean pressure causes the anisotropy to decrease, while the shear component tends to increase anisotropy. Beyond the peak point, both shear and mean pressure tend to decrease the anisotropy. Therefore, in order to obtain a true measure of such anisotropy, we have to include the contribution due to mean pressure. Figure (6.8a) is re-drawn in Figure (6.9) to show this effect. Hydrostatic component of $M_{anis}$ is estimated from $M_{anis}$ versus $\sigma_0$ plot for the HC test. First, $\sigma_0$ during the CTC path is found knowing $\tau_{oct}$. Corresponding to this $\sigma_0$, $M_{anis}$ is estimated from Figure (6.4). This variation is superposed on $M_{anis}$ as observed in the Figure (6.9) to obtain the net $M_{anis}$.

Figure (6.10) show a comparison of $M_{anis}$, $V_{anis}$ and $A_{anis}$ for the CTC30 test described in Chapter 4. It is seen that the values of $M_{anis}$, $V_{anis}$ and $A_{anis}$ show similar trend along the virgin curve. However, an increase in the values of $V_{anis}$ and $A_{anis}$ are observed up on loading and unloading to a same stress state. In this test also $M_{anis}$ due to shear is separated from that due to the mean pressure, using the procedure described earlier. Figure (6.11) shows such a decomposition. It is seen from the figure that the hydrostatic component of $M_{anis}$ is very less, as the mean pressure during CTC30 test is very large.

Figure (6.12) corresponds to the three measures of anisotropies for TE45 test. During this test, the mean pressure is kept constant and the computed $M_{anis}$ increases initially and decreases at high value of $\tau_{oct}$ (Figure 6.12a). This decrease in anisotropy is not due to change in mean pressure, but essentially due to re-orientation of particles during shear. In this figure, $M_{anis}$ is computed by the $\delta_1$ model and to it $M_{anis}$ value at the end of HC phase of the test is added. In this test also, the attenuation anisotropy shows a very good trend as that of $M_{anis}$. 
Figure 6.9 Decomposition of $M_{anis}$ to Hydrostatic and Shear Components for CTC20 Test

$\tau_{oct}$, psi
Figure 6.10 Variation of Mechanical and Ultrasonic Anisotropy for CTC30 Test
Figure 6.11 Decomposition of $M_{anis}$ to Hydrostatic and Shear Components for CTC30 Test
Figure 6.12 Variation of Mechanical and Ultrasonic Anisotropy for TE45 Test
Figure (6.13) shows the results for TC30 test. Here, $M_{\text{anis}}$ increases initially, reaches a peak value and then decreases. In this test also, the decrease of the mechanical anisotropy at a very large value of $\tau_{\text{oct}}$ is essentially due to the re-orientation of particles due to shear. In this test also the attenuation anisotropy show similar trend as that of the mechanical anisotropy.

Figure (6.14) shows the test results for the RTE30 test. In this test, the $V_{\text{anis}}$ and $A_{\text{anis}}$ increase with the $\tau_{\text{oct}}$. However, $M_{\text{anis}}$ shows an initial increase followed by a decrease. In this test also, loading and unloading to a same value of $\tau_{\text{oct}}$ result in higher values of ultrasonic anisotropies.

6.5 Correlation Functions

Based on the results presented in this chapter, it can be concluded that a combination of mechanical (destructive) tests and ultrasonic (NDT) provides information about enhanced understanding of the material anisotropy. The quantification of material anisotropy suggests that the mechanical anisotropy (due to strains) compares very well with the ultrasonic anisotropy. Development of correlation functions between the two is therefore feasible. In developing correlation functions for anisotropy the variation of mechanical and ultrasonic anisotropies with the octahedral shear stress (as discussed in section (6.4)) is to be considered. In these correlation functions, the mechanical anisotropy is expressed in terms of velocity anisotropy or attenuation anisotropy or a combination of both. Further, such correlation functions should be as simple as possible, in order to be used in practice.

6.5.1 Correlation functions for initial and induced anisotropy

The correlation functions for the mechanical anisotropy in terms of ultrasonic anisotropies is defined by,

$$M_{\text{anis}} = f(V_{\text{anis}} \text{ or/and } A_{\text{anis}})$$

$$M_{\text{anis}} = A_1 V_{\text{anis}} + A_2 V_{\text{anis}}^2 \quad (6.4a)$$
Figure 6.13 Variation of Mechanical and Ultrasonic Anisotropy for TC30 Test
Figure 6.14 Variation of Mechanical and Ultrasonic Anisotropy for RTE30 Test
where, \((A_1, A_2), (B_1, B_2)\) and \((C_1, C_2, C_3 \text{ and } C_4)\) are the material parameters relating the mechanical anisotropy with the ultrasonic anisotropies and are determined using the least square procedure. In Equations (6.4) \(V_{anis}\) and \(A_{anis}\) correspond to the experimental values, while \(M_{anis}\) corresponds to either experimentally determined value or the value as given by the \(\delta_1\) model. In developing these functions, the virgin part of the loading curve is considered. Selection of the appropriate correlation function depends on how well these functions predict \(M_{anis}\) for known values of \(V_{anis}\) and \(A_{anis}\). The procedure used to find the constants which define the correlation functions is as follows.

Step 1. Select experimentally determined values of \(M_{anis}, V_{anis}\) and \(A_{anis}\) at various values of \(\tau_{oct}\) along the virgin part of the CTC30 test and compute constants \((A_1, A_2), (B_1, B_2)\) and \((C_1, C_2, C_3 \text{ and } C_4)\) using least square procedure.

Step 2. Predict \(M_{anis}\) values for the same test along the virgin loading path and also along unloading and reloading paths.

step 3. Select Equations (6.4a) or (6.4b) or (6.4c) as the appropriate form of correlation functions, whichever gives the best prediction.

In the present investigation, the correlation constants for CTC30 test in Step 1. are:

\[
\begin{align*}
(A_1 &= 7, \quad A_2 = 200), \quad (B_1 = 18, \quad B_2 = 696) \quad \text{and} \\
(C_1 = -81, \quad C_2 = 663, \quad C_3 = 331 \quad \text{and} \quad C_4 = 317)
\end{align*}
\]

Figures (6.15), (6.16) and (6.17) show the predictions of \(M_{anis}\) for the CTC30 test using Equations (6.4a), (6.4b) and (6.4c), respectively. It is observed that the expressions (6.4a) and (6.4b) show good match with the experimental values.
Figure 6.15 Comparison of predicted $M_{anis}$ using $V_{anis}$ and Experimental $M_{anis}$ for CTC30 Test
Figure 6.16 Comparison of predicted $M_{anis}$ using $A_{anis}$ and Experimental $M_{anis}$ for CTC30 Test

$1 \text{psi} = 6.89 \text{kPa}$
Figure 6.17 Comparison of predicted $M_{anis}$ using both $V_{anis}$ and $A_{anis}$ and Experimental $M_{anis}$ for CTC30 Test
(Figures (6.15) and (6.16), respectively) and therefore it can be concluded that the Equations (6.4a) and (6.4b) are indeed suitable forms of correlation functions.

An important point to be noted here is that \((A_1, A_2), (B_1, B_2)\) and \((C_1, C_2, C_3\) and \(C_4)\) have been obtained based on one test. For the generality of correlation functions, we should include a number of stress paths. However, as such tests are not available, we can use the model to predict \(M_{anis}\) and use the same to determine \((A_1, A_2)\) and \((B_1, B_2)\). Here CTC30, TE45 and TC30 are used to determine constants. The resulting correlation functions are,

\[
M_{anis} = 10 V_{anis} + 3.6 V_{anis}^2
\]  \hfill (6.5a)

\[
M_{anis} = 21 A_{anis} + 52 A_{anis}^2
\]  \hfill (6.5b)

Using these correlation functions the \(M_{anis}\) values are back predicted. Figures (6.18), (6.19) and (6.20) show the back predictions for CTC30, TE45 and TC30 tests. It is observed that the values from Equations (6.5) compares well with the values obtained from the model. Further, Equations (6.5) are used to predict mechanical anisotropy during the CTC20 test which was not used to find these constants. Figure (6.21) shows the comparison between the predicted and model values of \(M_{anis}\).

6.6 Potential Applications

**In situ mechanical anisotropy**

Although there has been considerable amount of research on laboratory and field investigation of geologic materials, still not a single technique can quantify the initial anisotropy, effectively. However, the proposed correlation functions can be used to quantify the initial anisotropy of the material as follows.

Consider elements of geologic material under a combination of stresses (Figure 6.22). If a sample is taken from any of this elements, it could show
Figure 6.18 Comparison of predicted $M_{anis}$ and Model $M_{anis}$ for CTC30 Test
Figure 6.19 Comparison of predicted $M_{anis}$ and Model $M_{anis}$ for TE45 Test
Figure 6.20 Comparison of predicted $M_{\text{anis}}$ and Model $M_{\text{anis}}$ for TC30 Test
Figure 6.21 Comparison of predicted $M_{\text{anis}}$ and Model $M_{\text{anis}}$ for CTC20 Test
Figure 6.22 Prediction of in-situ Mechanical Anisotropy
anisotropic response due to its past history of loading. In order to quantify the initial (mechanical) anisotropy, the correlation functions can be used. First an ultrasonic test is performed in the field, at a point very close to the element being considered and the velocities and attenuations in the three orthogonal directions are recorded. The velocity anisotropy \( V_{\text{anis}} \) and ultrasonic anisotropy \( A_{\text{anis}} \) are computed using Equations (6.2) and (6.3), respectively. These values along with appropriate values of \( (A_1, A_2) \) and \( (B_1, B_2) \) are used in Equations (6.4a) and (6.4b) to obtain the mechanical anisotropy in the field.

**Quantification of initial anisotropy in constitutive models**

One of the setbacks in using the complex anisotropic constitutive models is the lack of information on the mechanical anisotropy values at the beginning of the test. However, if ultrasonic test results are available then the mechanical anisotropy can be estimated using the correlation functions. Using this value of the mechanical anisotropy, constitutive model is fully defined and the same can be applied for predicting the realistic response of the geologic material.
CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

This dissertation focuses its attention primarily on the development of a NDT procedure for the characterization of induced anisotropy in geologic materials and to compare, quantify and correlate such response with the anisotropic response as predicted by the constitutive model. Herein, the ultrasonic (NDT) method is used as a tool for quantifying the anisotropic response of the material and the $\delta_1$ model of the HISS series of models is used to describe the mechanical anisotropy.

An unique and novel testing procedure which includes three-dimensional mechanical (destructive) testing combined with ultrasonic (NDT) testing of cubical (cemented sand) samples under various stress paths has been developed. This involved the modification of existing stress-controlled truly triaxial device to incorporate ultrasonic testing and use of a state-of-the-art data acquisition system to acquire the data during the test.

Extensive laboratory tests have been performed on cemented sand under different stress paths of loading, unloading and re-loading. Mechanical response is presented in the form of stress-strain and volumetric responses, while, the ultrasonic response is presented in the form of wave signatures, velocities and attenuations. Also, special tests were performed to observe experimentally the anisotropic response of a material in shear stress paths.

The quantification of mechanical anisotropy is made by using the $\delta_1$ model, while, the ultrasonic velocity and attenuations are used to define the ultrasonic anisotropies. The parameters which define the $\delta_1$ model are determined based on the test results, and the suitability of the model is verified by back-predicting the tests. Correlation functions for initial and induced anisotropies in terms of the velocity anisotropy and the attenuation anisotropy have been developed, based on the observed data and on the principles of mechanics. The potential applications of such functions are also discussed.
Based on the work presented in this dissertation following conclusions are made:

1. the anisotropic response of an initially anisotropic material can be characterized by ultrasonic technique. The method also gives a physical measure of internal changes occurring in the material due to the application of stresses.

2. the mechanical (destructive) anisotropy can be quantified using the $\delta_1$ model of the HISS series of models.

3. development of correlation functions between the mechanical anisotropy and the ultrasonic anisotropy are feasible, and the simple nature of such functions has promising applications to the field.

4. the initial and induced anisotropy of the material can be determined by knowing the ultrasonic velocities and attenuations, and

5. the gradual demise of mechanical and ultrasonic anisotropies during hydrostatic loading, mechanistically proves the soundness of proposed definition.

7.2 Recommendations

Some recommendations regarding future research as related to the present work are:

1. correlation functions have been developed using the mechanical anisotropy as obtained by the simple non associative model for monotonic loading. However, the method can be extended to complex models such as, anisotropic hardening ($\delta_2$) models, which considers the effect of cyclic loading also,

2. in obtaining the ultrasonic response only P-waves are used. However, if the similar tests are performed with S-waves also, results could be applied for describing the anisotropic response. and

3. tests have been performed using the stress controlled cubical device. However, strain controlled triaxial and ultrasonic tests can give insights into the phenomenon strain softening due to damage, micro-cracks.
LIST OF REFERENCES


