TECHOLOGY DIGEST

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# LABORATORY INVESTIGATION OF SOFT SUBGRADE FAILURES UNDER REAPEATED LOAD APPLICATIONS

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## Summary

The Association of American Railroads (AAR) and the University of Oklahoma conducted laboratory tests to quantify the failure mechanism of soft subgrade soil under repeated load applications aiding in the selection of the most effective remedies. Test results showed that soil dynamic strength under repeated loading was directly related to the degree of saturation and confining stress applied to the soil. For the low track modulus (LTM) subgrade soil, installed at the Facility for the Accelerated Service Testing (FAST) at the Federal Railroad Administration's Transportation Technology Center (TTC), a correlation was derived to determine soil dynamic strength as a function of soil physical and stress conditions. The AAR's business activity at TTC is now known as Transportation Technology Center, Inc., a subsidiary of the AAR. The FAST program is a cooperative FRA/AAR activity.

Under heavy axle loads (39-ton or HAL) and with a conventional track structure, the LTM test section could not sustain normal track geometry and required surfacing every 10 to 30 million gross tons (MGT). By using undisturbed soil samples taken from the test subgrade, laboratory tests were performed under simulated field conditions to determine the performance of the soft subgrade under repeated load applications.

The actual variation of degree of saturation from 90 to 99 percent for the soil samples tested had a tremendous effect on soil sample failure. Higher confining stress applied to soil samples led to higher soil strength in resisting excessive soil deformation and failure. A comparison between laboratory test results and field measurements in the LTM indicated that subgrade stresses under the HAL train frequently exceeded soil dynamic strengths, especially at the nearly saturated locations. Therefore, the most effective remedies, without replacing and improving subgrade soil, should provide subgrade stress reduction, minimize free water (which tends to increase soil degree of saturation) and increase confinement to the subgrade.

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## INTRODUCTION AND CONCLUSIONS

The Association of American Railroads and the University of Oklahoma conducted laboratory tests to quantify the failure mechanism of a soft subgrade soil for the benefit of selecting the most effective remedies. Test results showed that soil strength under repeated loading (or soil dynamic strength) was directly related to the degree of saturation and confining stress applied to the soil.

Previously, a low track modulus (LTM) test section at the Facility for Accelerated Service Testing (FAST) could not sustain proper track geometry conditions under 39-ton heavy axle loads (HAL). With a conventional track structure built on a soft subgrade, the LTM section required surfacing every 10 to 30 million gross tons (MGT). By using undisturbed soil samples taken from the test subgrade, laboratory tests were performed under simulated field conditions to determine the performance of the soft subgrade. For this subgrade soil, a correlation was derived to quantify soil dynamic strength as a function of soil physical and stress conditions. Laboratory tests also showed how soil samples exhibited lower strength under repeated loading than under a single static loading

For the soil samples tested, the actual variation of degree of saturation from 90 to 99 percent made a tremendous difference in whether a soil sample would fail under similar stress conditions. Higher confining stress applied to the soil samples led to higher soil strength in resisting excessive soil deformation and failure. A comparison between laboratory test results and field measurements of LTM subgrade stresses indicated that subgrade stresses under the HAL train frequently exceeded soil dynamic strengths, especially at the nearly saturated locations. Thus, subgrade stress reduction, reduction of soil degree of saturation, and confinement to the subgrade should all be considered in selecting a remedy to soft subgrade problems.

## TESTS SIMULATING FIELD CONDITIONS

To explain the actual subgrade performance as observed at the LTM test section, laboratory tests were designed and set up to closely represent field subgrade soil and load conditions. First, undisturbed soil samples were taken at various locations of the LTM section using thin-walled Shelby tubes. Then, static and cyclic tri-axial load tests were performed under various soil and load conditions. Exhibit 1 summarizes the cyclic tri-axial tests conducted. The ranges of stresses applied on soil samples were chosen based on field measurements of soil stresses in the LTM.[1] In addition, tests were performed to obtain other soil physical and index properties.[2]

**Exhibit 1. Summary of Cyclic Tri-axial Tests**

| Test No. | Moisture content (percent) | Degree of Saturation (percent)** | Confining stress (psi) | Deviator stress (psi) | Failed? |
|---|---|---|---|---|---|
| 1 | 31.6 | 92.1 | 5 | 5 | no |
| 2 | 34.0 | 90.5 | 2 | 8 | no |
| 3 | 35.3 | 100* | 2 | 8 | yes |
| 5 | 33.4 | 100* | 5 | 8 | yes |
| 6 | 29.1 | 100* | 5 | 5 | no |
| 7 | 32.5 | 92.4 | 3.2 | 11 | yes |
| 8 | 36.1 | 96.9 | 3.2 | 8 | yes |
| 9 | 34.8 | 97.6 | 5 | 8 | yes |
| 10 | 33.8 | 93.5 | 5 | 5 | yes |
| 11 | 33.9 | 93.7 | 2 | 5 | no |
| 12 | 37.8 | 98.9 | 2 | 5 | yes |

* Via back-pressure saturation

** Initial degree of saturation except No. 3, 5, 6

Degree of saturation is defined as the percentage of soil voids filled with water; whereas, soil moisture content is defined as the ratio of water weight to dry soil weight expressed in percentage. As shown in Exhibit 1, the initial degree of saturation for the soil samples taken from the LTM subgrade varied from 90 to 99 percent, while their natural moisture content varied from 29 to 38 percent.

Exhibit 2 illustrates the definitions of confining and deviator stresses. In a static tri-axial test, the deviator is increased until the soil sample fails. In a cyclic tri-axial test, the deviator stress is cycled between 0 and a predetermined magnitude while the confining stress remains constant. Soil shear strength is defined as half of the maximum deviator stress; i.e., $(\sigma_1 - \sigma_3)/2$, that a soil can withstand without failure. Sometimes, soil compressive strength is used, which has a value twice as much as shear strength (i.e., the maximum deviator stress a soil can resist). Static strength is obtained from a static load test; whereas, dynamic strength is determined from a cyclic load test.

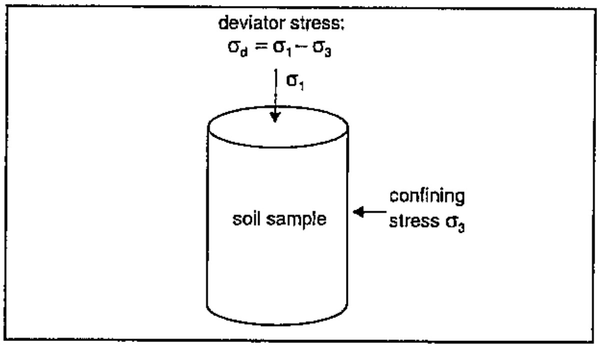

**Exhibit 2. Definitions of Confining and Cyclic Deviator Stresses**

## RESULTS AND DISCUSSIONS

Static soil strength was determined first. Exhibit 3 shows stress-strain relationships for three soil samples tested under static loading conditions. As shown, static soil strength depended on confining stress. Higher confining stress led to higher soil strength. For the three confining stresses of 5, 5.5, and 10 psi, soil compressive strength was found to be 9.0, 9.4, and 12.2 psi, respectively.

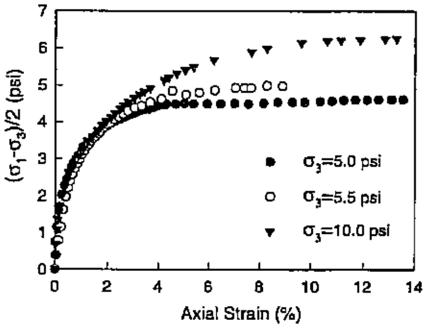

**Exhibit 3. Stress-Strain Behavior from Static Tests**

Exhibit 4 gives a comparison of stress-strain relationships between stable and unstable soil condition for the tests conducted under cyclic loading conditions. Exhibit 4a depicts an unstable soil behavior under cyclic loading, resulting in the accumulation of increasing permanent strain. Ten cycles of deviator stress led to a total cumulative strain of 2.6 percent, with a permanent strain of approximately 2.2 percent. On the other hand, Exhibit 4b shows a stable soil behavior under cyclic loading where the incremental permanent strain decreased with each cycle of deviator stress. After 200 cycles of deviator stress, the total cumulative strain was less than 0.5 percent, with a permanent strain of only 0.2 percent.

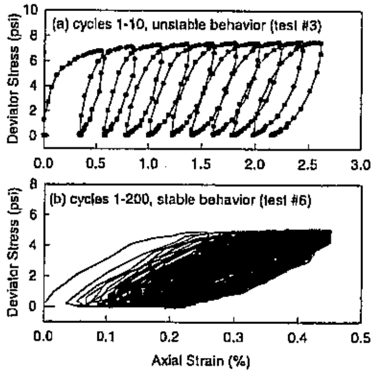

**Exhibit 4. Comparison of Stable and Unstable Soil Behaviors**

Obviously, soil performance depends on the magnitude of cyclic stress applied to the soil. Higher cyclic deviator stress will result in higher cumulative deformation or a higher likelihood of soil failure. Exhibit 5 shows a comparison of the results obtained using two different deviator stresses. The soil sample did not fail under a cyclic deviator stress of 5 psi, as evident by a stabilizing cumulative deformation behavior.

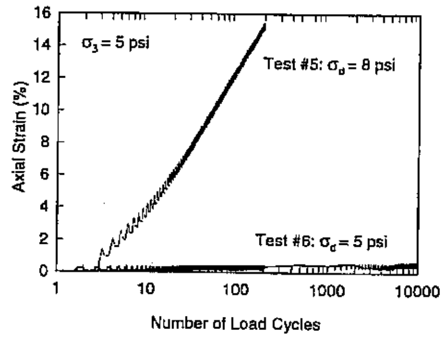

**Exhibit 5. Soil Cumulative Deformations under Different Cyclic Deviator Stresses**

However, under a cyclic deviator stress of 8 psi, the other soil sample with similar physical conditions failed, as indicated by the increasing cumulative deformation under cyclic loading. The results in Exhibit 5 also indicate that with a confining stress of 5 psi, the dynamic soil compressive strength was between 5 and 8 psi. This was lower than the soil static compressive strength of 9 psi (Exhibit 3)obtained under similar confining stress and drainage conditions.

Effects of confining stress and degree of saturation on soil performance were examined and are listed in Exhibit 1. These results are also summarized in Exhibit 6. As shown, dynamic shear strength is normalized by the confining stress and is plotted as a function of degree of saturation. For a total of 11 cyclic tests, a boundary was drawn to divide the failed and stable soil samples under repeated loading. This boundary represents dynamic soil strength under various conditions, which can be expressed by the following equation:

$$\left(\frac{\sigma_1 - \sigma_3}{2}\right) = (17.1 - 0.167S)\sigma_3$$

where S = saturation degree (percent). Note that compressive strength can be obtained by doubling shear strength. This equation can then be used for determining soil dynamic strength for the LTM subgrade soil under various soil and stress conditions.

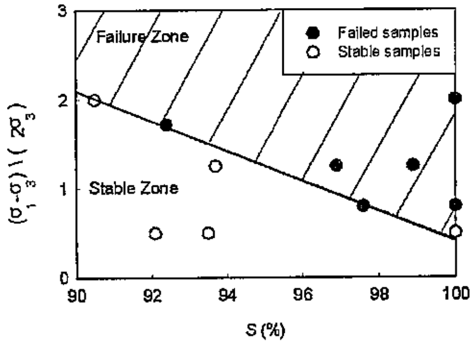

**Exhibit 6. Relationship between Soil Dynamic Strength, Degree of Saturation, and Confining Stress**

A comparison between soil dynamic strengths, as indicated by the above equation, and field measurements of subgrade stresses indicates that the magnitudes of repeated deviator stress under the HAL train frequently exceeded soil dynamic strengths in the LTM zone, especially at the nearly saturated subgrade locations.[1] Exhibit 7 shows an example comparison between the subgrade deviator stresses measured at one LTM subgrade location at various MGT levels and three possible soil dynamic strengths. As shown, under a confining stress approximately 5 psi, the 90th percentile of repeated deviator stress at this measurement location exceeded soil dynamic strength, when degree of saturation was at or above 99 percent.

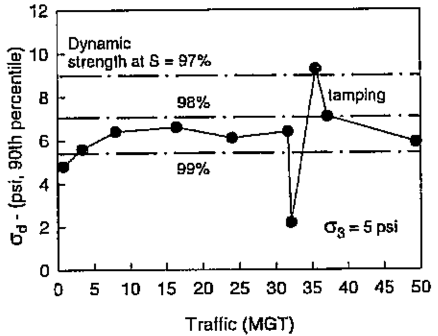

**Exhibit 7. Comparison between Subgrade Stresses and Soil Dynamic Strengths**

To correct the subgrade problem as observed in the LTM test section, the most effective remedies should therefore provide subgrade stress reduction, minimize free water that tends to increase soil degree of saturation, and increase confinement to the subgrade.

## REFERENCES

1. Li, D., Read, D. and Chrismer, S. "Effects of Heavy Axle Loads on Soft Subgrade Performance," *Technology Digest* TD97-020, Association of American Railroads, July 1997.

2. Miller, G., Zaman, M. and Teh, S. "Laboratory Investigation of Soft Railroad Subgrade Soil Behavior under Repeated Load Applications," Report No. ORA-5989, University of Oklahoma, Norman, Oklahoma, 1998

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