The 19th International Mining Congress and Fair of Turkey, IMCET2005, Izmir, Turkey, June 09-12, 2005

Soft Ground Reaction To Cyclic Loading By Large Mobile Mining Equipment

A.D. Sharif-Abadi
Ph.D. Graduate Student, AEGIS research group, University of Alberta, Edmonton, Canada.

T.G. Joseph
Director AEGIS, University of Alberta and Principal Engineer, JPi, Edmonton, Canada.

ABSTRACT: Essentially there are two different types of ground equipment loading condition in the surface mining industry: Systems that rely on tracks, roller paths, rollers and side frames and those that rely on tires, rims and suspension systems for motion. In both cases, the footprint created is variable, providing a ground loading that is a function of the kinematics of the machine and the ground performance properties. Marrying the two to get a complete picture of the ground - equipment interactions is a complex model of inter-related performance profiles. This paper looks at the cyclic loading phenomenon of soft ground in relation to the action of large mobile mining equipment, where footprint area, loading (change in g level) and relative stiffness of components from ground to frame are essential in understanding adverse operating conditions. A geotechnical overview of ground performance due to this type of loading condition will be presented.

1 INTRODUCTION AND BACKGROUND

To reduce the cost of mining, mining companies opt for large mobile mining equipment. In the oil sand, loading and hauling of material results in the biggest cost to the final product. Soft ground conditions, especially those of oil sand, have unique properties that have been widely studied to give a better understanding of that material behavior in various situations. Construction of large mobile equipment for soft ground adverse operations requires a good understanding of the interaction with adverse ground and vice versa. Laboratory and field tests aid a better understanding of this material. In this case, several triaxial tests were done. In addition, a simple plate load test was designed for a field testing equivalent.

Joseph (2003) reported that after only a few cycles, truck and shovels operating on soft-ground will become less stable. Trucks in summer are frequently loaded with less than their nominal payload due to poor rolling resistance conditions. Even with lower payloads the cycled ground after only a few passing trucks is unable to support the weight of the truck. In summer, ground has a lower stiffness compared to tire and suspension stiffness, consequently ground deformation is greater than that of the tire or suspension resulting in ground undulation. Rutted ground causes rack, roll and pitch truck motion that cause frame, suspension and tire fatigue.

For shovels, rocking during face activity in soft ground conditions after a number of cycles can result in sinking. In the oil sand case, ground softening occurs rapidly due to cyclic pressures (Joseph, 2002).

2 BASIC CONCEPTS AND ASSUMPTIONS

1. Oil sand beneath mobile equipment is already broken, described as loose and unlocked. However according to the coarse shape of the material, there remains considerable friction between particles.
2. As material is already broken and loose, there is no early discernable peak value with increasing strain, and the material expresses post-peak behavior before reaching a residual value.
3. The bitumen and water content comprising the oil sand fluid content remains relatively constant within a given mining block.
4. Oil sand is homogenous and uniform allowing the use of an elastic approach for analyzing this material despite its highly fragmented nature.
5. Pore pressures dissipate rapidly. Moreover, oil sand is not fully saturated, so pore pressures are

not a major concern in calculating the effective stress beneath the equipment.

6. As the material is broken near surface any exsoluting gas has already left the material and it is thus a negligible consideration to the bearing capacity of material the ground.
7. Figure 1 shows the concept that the pseudo-elastic stiffness of the post-peak reduces with increasing number of cycles.

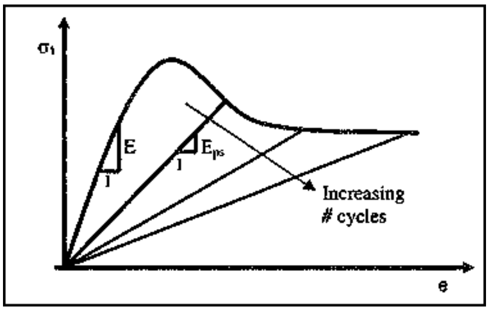

Figure 1 Modulus with # cycles (after Joseph, 2003)

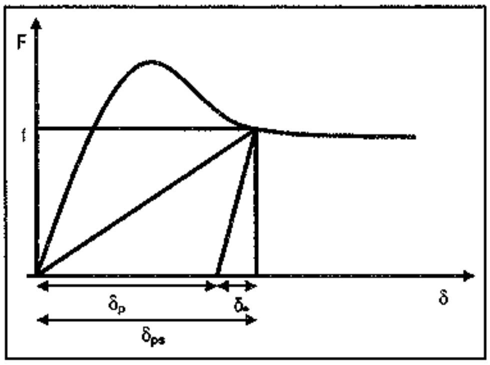

Figure 2 Total deformation (after Joseph, 2003)

8. The total deformation may be described as the sum of the elastic and plastic deformations, figure 2 and equation 1 :

$$\delta ps = \delta p + \delta e \qquad [1]$$

3 LABORATORY TRIAXIAL TESTS

Several triaxial test were done on 8% bitumen samples with a strain rate set at 72x10"^{6} per minute with a density of 2.0 to 2.1 g/cm^3. As the material is broken and loose, the prepared samples for use in triaxial cells required compaction to reach close to the field density. Figure 3 shows the stress-strain curve results for these tests.

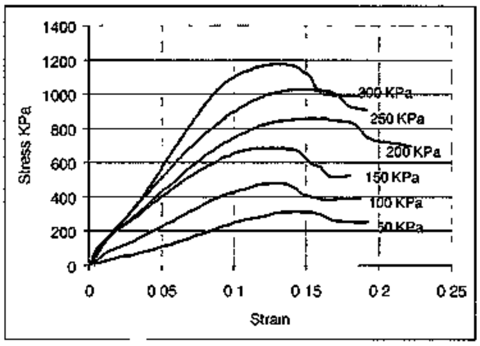

Figure 3 Triaxial test results for 8% oil sand

A peak strain of around 0.15, because of the low range of confining pressures applied revealed a linear relationship between <3\ and 03, equation 2:

a, = 0.27Ö3 - 33.5 kPa [2]

Further triaxial tests were performed on samples with 11 % bitumen content, figure 4. The strain rate was kept the same as before, with the only difference being using a hydraulic jack to compact the sample in a metal cylinder to reach the field density.

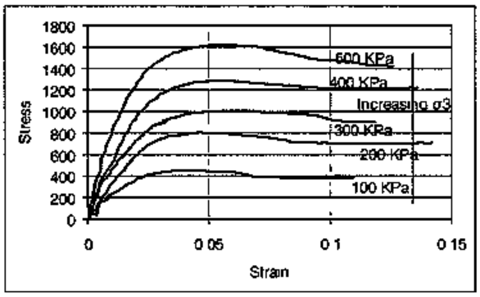

Figure 4 Triaxial test results for 11% oil sand

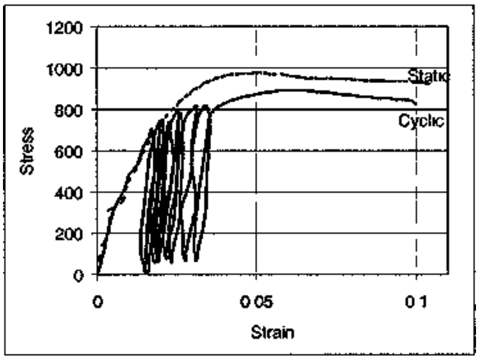

Figure 5 Laboratory cyclic triaxial at 03 = 300 kPa

In addition to static triaxial tests, three tests were done under cyclic loading at varying confining pressures. The aim of the cyclic loading tests was to show that large mobile mining equipment can induce early failure in underfoot materials leading to early residual values. Figure 5 shows the cyclic loading compared to the static loading for a 300 kPa confined sample, revealing a lower peak strength realization.

The purpose of the triaxial tests was to identify the induced confining pressure to compare with field tests and infer the field induced confinement. Softening of the ground with cyclic loading is the mechanism by which mobile mining equipment loads the ground.

4 FIELD TESTS

A cyclic plate load test was designed to help understand the behaviour of oil sand under the cyclic loading action of mobile mining equipment. Study of such ground behavior in a laboratory environment is difficult especially for near surface material. Figure 6 shows the field set up.

A hydraulic loading cylinder was attached to the rear hitch of a % ton light vehicle, actuated by a hand pump for simplicity. A load cell was placed between the hydraulic cylinder and plates of varying dimension as the contact surface with the ground. A linear extensometer was used to provide accurate ground deformation, referenced to a frame independent of the loading system and the light vehicle. The plate was then loaded for a given period of time, unloaded and reloaded to effect the cyclic motion reminiscent of mining equipment loading frequencies. The output was recorded to a standard data acquisition system.

Tests were carried out with three different plate sizes. Table 1 shows the plate sizes and maximum stresses reached during the tests.

Table 1 Cyclic plate size and test information

Plate size class (cm)	Max stress (kPa)	Test time (minutes)
Large, 14.9	300	9:39
Medium 11.43	390	1:21
Small 7.62	930	2:00

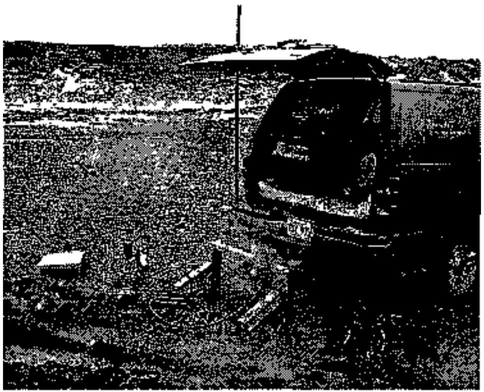

Figure 6 Cyclic plate load field test set-up

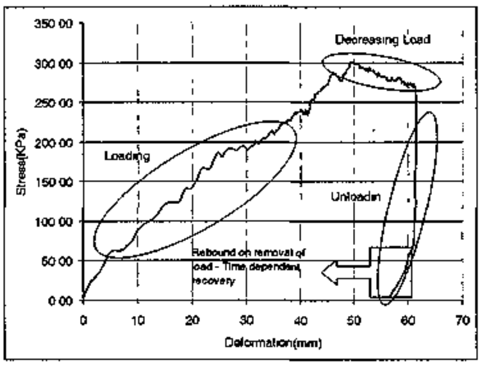

Figure 7 Stages of a single cycle plate load test

Confining pressure induced during the test is a function of plate size. Plastic deformation is also a function of induced pressure and the number of loading cycles. The rebound of the material after removing the load is time dependent and related to confining pressure. The different stages of the tests are shown in figure 7.

Figures 8 and 9 show pressure stiffness-deformation curves for loading and decreasing load stages, which show that stiffness decreases with increasing deformation and is independent of plate size.

Figure 10 illustrates the stress-deformation relationship for oil sand for a cyclic test of around 46 minutes duration and containing 7 cycles. Unloading and loading slopes are relatively constant. As oil sand has a viscoelastic behavior, the rebound cycle is time dependent.

Figure 11 shows the plastic and elastic deformation components of the cyclic test with respect to time, where the elastic deformation bounded, converging to a constant value.

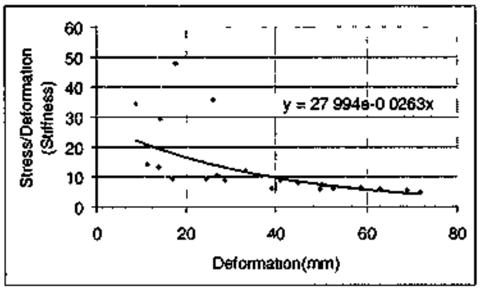

Figure 8 Changing ground stiffness during loading

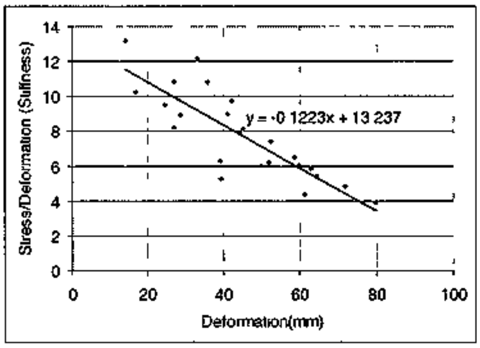

Figure 9 Changing stiffness during unloading

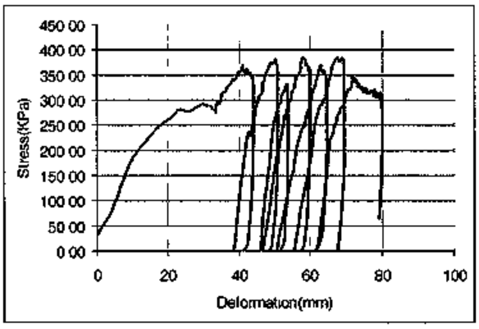

Figure 10 Stress-deformation curve for a cyclic test showing unloading-loading cycles

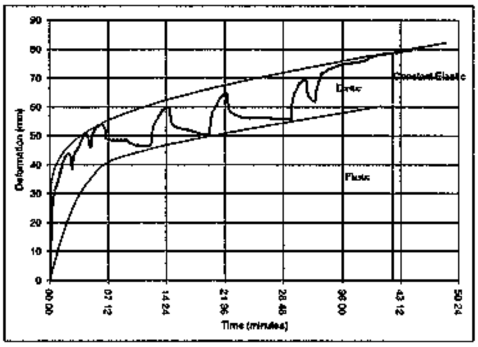

Figure 11 Plastic and elastic deformation

5 FIELD VERSUS LABORATORY TESTS

The main objective of comparing field and laboratory data is to evaluate the induced confining pressure in the field as a function of applied load. Solving this correlation is mathematically complex. Therefore, as a first approximation, matching the triaxial test curve to the plate load test curve was performed to give on estimation of the induced confining pressure by applied load. Figure 12 shows the matching of laboratory and field test data for two tests. The figure shows that the matched loading condition is related to the residual strength of the triaxial specimens. Not surprising considering the highly disturbed nature of the in-pit field material.

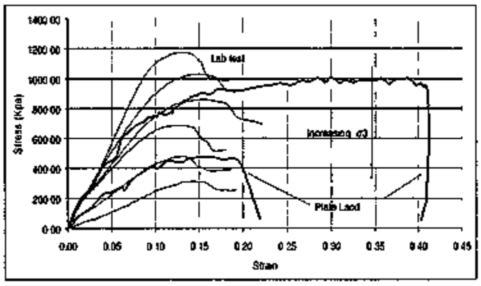

Figure 12 Comparison of field and laboratory data

This method gives us the ability to define a relationship between induced confining pressure and applied load. The induced confining pressure is effectively the horizontal stress in the field. Given this information it is possible to assign an appropriate confining pressure for numerical modeling purposes.

It is also possible to infer a Poisson's ratio from the ai - σ'3 relationship given the widely expected relation, equation 3.

$$\sigma_H = \left(\frac{\nu}{1-\nu}\right)\sigma_V \qquad [3]$$

Figure 13 yielded a value for Poisson's ratio, v, of 0.22, lower than expected from previous historical evaluation at -0.25 and industry use at 0.31.

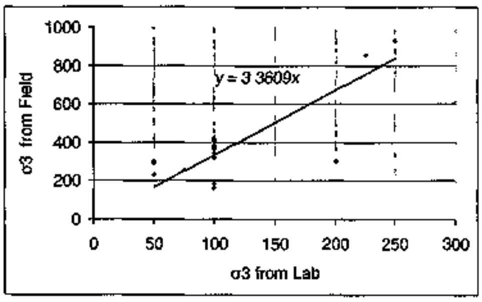

Figure 13 Ci versus a_3

6 MODELING OF A PLATE LOAD TEST WITH FLAC - AKIN TO A TRACK PAD

Numerical modeling of a plate load test allows the investigation of a simplified pseudo-elastic approach to predicting ground deformation during loading. Here the basic assumption is that oil sand is uniform and homogenous, such that load deformation behavior in akin to elastic, although permanent deformation occurs. Flac 2-D was used to model the plate and ground, as the software provides user defined constitutive modeling. Three different plate sizes were modeled. Holding Poisson's ratio constant and varying the pseudo-elastic modulus, (inherently including any changes in Poisson's ratio), with applied confining stress such that E = (25*ff3 +1465), the following results were found.

The larger plate results showed that a confining pressure of around 50 kPa is induced with deformation at the point the load reaches a constant value, and is accurate to ±15% of actual field values. Figures 14 through 17 show the output vertical and horizontal stress, vertical deformation, and 03 for the large plate configuration.

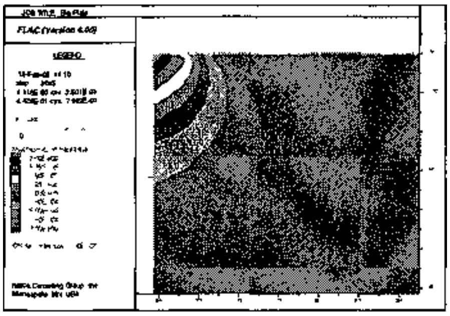

Figure 14 Flac 2-D output vertical stress

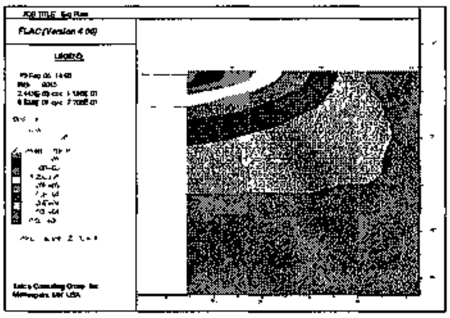

Figure 15 Flac 2-D output horizontal stress

The output from the Flac 2-D model yielded the same induced horizontal stresses estimated from the laboratory - field physical data comparisons, and deformations + 15% of those measured in the field.

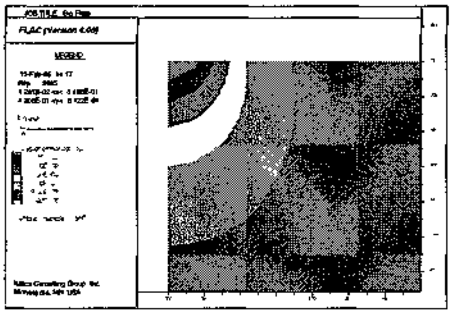

Figure 16 Flac 2-D output vertical deformation

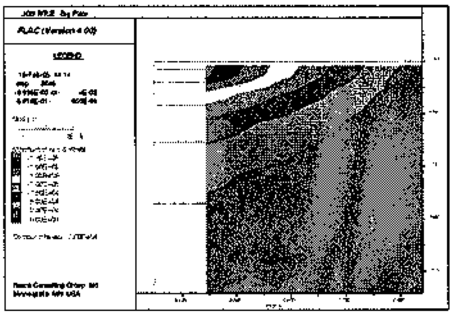

Figure 17 Flac 2-D output confining pressure σ_3

7 MODELING OF INDUCED GROUND STRESSES BELOW A HAULER TIRE

Matlab was used to estimate the induced horizontal stress in the oil sand due to the action of truck tire. Use was made of the Boussinesq assumptions for homogeneous, isotropic, weightless, elastic conditions in half space with a concentrated vertical load, which were considered appropriate for use for the assumed homogeneous oil sand material. Treating the ground material as pseudo-elastic allowed an estimation of the stresses to be made.

For an ultra class haul truck, such as a Caterpillar 797, where the tire-ground contact area ~ 1.3 m^2 at 1g loading, and given the gross vehicle of - 637 tonnes, such that each tire is loaded by - 1 MN.

For simplicity it was considered that the width of the truck compared to the tire is big enough such that one side of the truck does not influence the other, in terms of ground loading. An assumption that is not necessarily true for real duals, but certainly a reasonable approximation at this level of analysis.

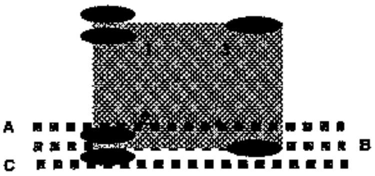

Figure 18 Sections referenced in Matlab output

The output from the Matlab analysis is referenced to the ground cross-section B as indicated in Figure 18. Figures 19 and 20 show the vertical, horizontal and principal stress output from this analysis.

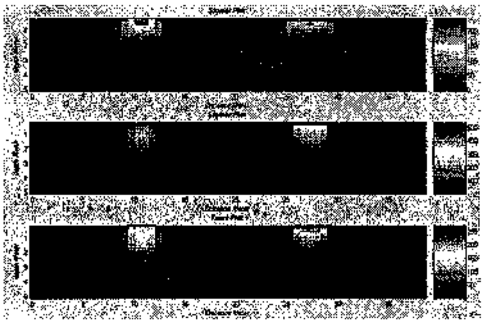

Figure 19 Vertical and horizontal stress; section B

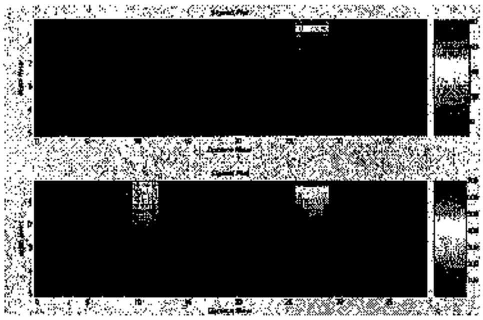

Figure 20 Principal stresses; section B

The Matlab output for horizontal stress prediction, given a known vertical stress, confirmed the output from the Flac 2-D analysis and was verified by the laboratory - field physical data acquired.

8 CONCLUSIONS

It has been shown that the induced horizontal stresses in soft ground, such as oil sand, can be inferred and predicted from the loading condition due to large scale mobile mining equipment operating at surface. This has been verified by correlations between the field and laboratory test data.

The assumption that the ground is homogeneous and can be treated in a pseudo-elastic fashion is made valid by the agreement between the two physical modeling and the two numerical modeling approaches employed.

A simple cyclic plate load test has been conceived and validated m the field, which may be used by the mine operator in verifying the suitable stability of soft ground before moving large mining equipment into the vicinity for operation Such simple use might determine deformational response of the ground for a know pressure loading due to the size of the equipment

Figure 11 shows that the elastic deformation of the ground is constant, despite the fact that the pastic deformation increases to a constant level at a large level of deformation

REFERENCES

Joseph, TG, Shanf-Abadi, AD and Shi, N, 2003, A broken material approach to modeling oil sand under dynamic load, Proceedings of the 4^{lh} International Conference on Computer Applications in the Minerals Industries (CAMI 2003), September 8 - 10, Calgary, Alberta, Canada

Joseph, T G , 2002, OsEIP The Oil sand Equipment Interactions Program, *CIM Bulletin,* 95, pp 58 - 61