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Building on Mine Spoil: New Approach Using Dynamic Consolidation and Pressuremeter Testing

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A combination of two well-known techniques of soil testing and soil improvement was used on an experimental section to test its ability to improve and test recent mine spoils. These techniques are pressuremeter testing and Dynamic Consolidation. The mine spoil is composed of 100 ft (33 m) of shales, tills, and loesses that were transformed by weathering action into a silty clay matrix. This silty clay holds in its mass an extremely large number of limestone boulders. The spoil, 10-15 years old, exhibits poor engineering characteristics and has not yet reached its self-bearing level. Pressuremeter tests were performed at all stages of the work. The depth of the boreholes was generally 50 ft (15 m), and a test was performed every 3 ft (1 m) down. The pressuremeter probe was protected by a slotted steel casing. The Dynamic Consolidation was performed with light equipment in order to test the technique economically on the top 35 ft of the spoil. Two trial areas were compacted and results were compared with those of a 20-ft (6-m) high earth-fill load test. Results show that improvement due to the Dynamic Consolidation is dramatic and two to eight times larger than the improvement induced by the earth-fill load test. The analysis of the results enabled the determination of a program to improve the entire mass of the fill so it can be used as a good foundation to support heavy construction on shallow foundations.

The construction of a large industrial plant with heavy loads and limited settlement tolerances on 100 ft (33 m) of a silty clay material with large boulders of limestone raises some serious foundation problems, both technical and economic. A new approach for testing and improving the engineering characteristics of the soil was developed and tested on site. The techniques involved were essentially pressuremeter testing and Dynamic Consolidation, both developed and performed in the field by Menard, Inc.

SITE GEOLOGY

The soil consisted of a heterogeneous mixture of shales, tills, and loesses transformed by weathering action into a silty clay material. It holds in its mass a large amount of big angular blocks of limestone. These materials were originally the overburden of a series of coal strata that were strip mined approximately 12 years ago. During the operation, the above mine spoils were dumped erratically on the site. The water table at the time was situated 35-ft (10.5-m) deep.

PROGRAM OF OPERATIONS

The test included three major activities:

1. Pressuremeter testing before, during, and after the Dynamic Consolidation work,
2. Execution of Dynamic Consolidation, and
3. Pressuremeter testing through an earth-fill load test to calibrate the results.

Pressuremeter Testing

The pressuremeter is an instrument for in situ measurements of soil load and deformation parameters. It consists of two main components (Figure 1):

1. The probe is a cylindrical metal body covered by a radially deformable cover. It is formed of three cells (see Figure 2). The central or measuring cell is filled with water under controlled pressure.
2. The control unit regulates volumes and pressures applied on the different cells.

The probe is placed within a previously drilled borehole or driven into the ground at the desired elevation. Pressure is then applied in equal increments and the corresponding volume variations are noted at 30- and 60-s intervals. By plotting volumes versus pressures at each increment, an in situ stress-strain curve is obtained (see Figure 2). Some of the engineering characteristics of the soil that are derived from the test are the limit pressure Pl, or the pressure at which failure occurs. It reflects directly the bearing capacity of the soil. The test also gives the modulus of deformation (E) from which settlements can be calculated.

All tests were carried out by using a GA-type Menard pressuremeter. In order to avoid frequent puncture, the probe was inserted into a slotted casing. The casing was driven into the ground by using an Atlas Copco Roc 601 drilling rig and O.D. method. Boreholes were usually terminated at 50-ft (15-m) depth. Tests were carried out every 3 ft (1 m).

Dynamic Consolidation

Dynamic Consolidation is a method patented and developed in 1969 by the late French engineer Louis Menard. It improves the engineering properties of in-place soils at depth, both above and below ground water table, both onshore and offshore. The method consists of providing large energy impacts at the ground surface. This is done by dropping steel tampers 10-200 tons in weight from heights of 60-120 ft.

In any type of unsaturated material, the shock waves cause compaction as in a Proctor test. In submerged soils, P-wave first causes partial-to-full liquefaction and the S-wave and the Raleigh wave rearrange the soil grains structure into a denser state. Improvement has been achieved in materials that range from rock fill to clayey silt and building or domestic refuse. The results of treatment by Dynamic Consolidation are dramatic and immediate. Strength in terms of bearing capacity is typically improved by a factor of 2-4. Compressibility in terms of total and differential settlements can be reduced by a factor of 3-10. An essential part of the Dynamic Consolidation service is an intensive program of field and laboratory tests. On the basis of these tests energy requirements and construction sequences are planned.

The budget available for the test section did not allow for the mobilization of special heavy rigs capable of improving the soil down to 100 ft (33 m). Therefore, the test was carried out with a modified 150-ton crawler crane dropping a 15-ton pounder from 65 ft (see Figure 3). That type of equipment can usually treat the ground down to 30 ft (9 m). Careful analysis of results enables determination of the improvement that could be obtained at a greater depth by using heavier equipment. This is done by using empirical formulas established on numerous sites around the world.

Earth Fill Load Test

An earth fill load test 22 ft (6.7 m) high and 80x80 ft (24x24 m) square top was available on the site. Settlements of the soil below the embankment had been monitored by using 15 settlement gauges dropped in four different boreholes at different elevations. The deepest gauge was located at 75 ft (22.5 m) below the original ground surface. At that point a pressuremeter boring was made in the mine spoil through the embankment. Tests were carried out every 3 ft (1 m) down to a depth of 106 ft (38 m).

Figure 1. Pressuremeter equipment.

RESULTS OF EARTH FILL LOAD TEST

Settlements measured under the earth fill are plotted on Figure 4. They indicate that compression occurred down to 113 ft (34 m). The pressuremeter profile, especially the modulus of deformation, shows that, in fact, the improvement due to the static load was limited to 36 ft (11 m). Immediately underneath the foundation the stress applied on the surface induces a volume change in the soil and, therefore, the development of a consolidation process (increases of the three principal stresses). Below that area, only angular deformations occur to induce settlements but no consolidation (only one principal stress increases with the load).

Compariso between the settlements that occurred underneath the earth fill load test and those calculated for the same load by using the pressuremeter results enables the determination of some important parameters, such as the so-called structure coefficient, which varies according to the type of soils and its degree of consolidation. This parameter also represents the ratio between the pressuremeter deformation modulus and the constrained modulus. The structure coefficient was found to be equal to 0.55.

DYNAMIC CONSOLIDATION

The Dynamic Consolidation technique was tested in two different areas. They were approximately 500 ft (150 m) apart and were both cleared of vegetation and leveled prior to the treatment.

Area A

Treatment on area A was performed in five phases. Phases 1 and 2 consisted of pounding a 20x20 ft (6x6 m) square grid. Phases 3 and 4 consisted of pounding a 20x20 ft intermediate grid (prints in between prints of the primary grid). Phase 5 consisted of

Figure 2. Typical pressuremeter curve.

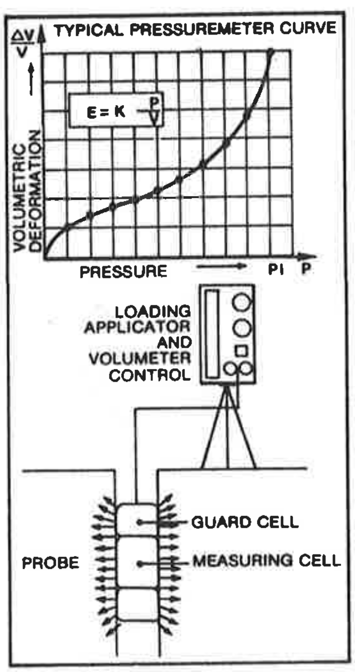


Figure 3. Dynamic consolidation rig.

an ironing phase where the pounder was dropped once on a 10x10 ft (3x3 m) square grid. A total energy of 304 Mg•m/m² was necessary to compact this area. (The energy consists of the weight of the hammer in megagrams multiplied by the drop height in meters and divided by the grid surface in square meters.)

Area B

Treatment of area B was performed in four phases. Phase 1 was done on a 40x40 ft (12x12 m) grid; Phase 2 on a 40x40 ft intermediate grid. Phase 3 was done on a 20x20 ft (6x6 m) grid superimposed on the previous ones. Phase 4 was an ironing phase on a 10x10 ft (3x3 m) grid. The energy necessary to compact this area was equal to 330 Mg•m/m².

Results

The clayey nature of the mine spoils necessitated the presence of a 2-ft (0.6-m) thick rock-fill working platform on both areas. This rock fill was used primarily to backfill the craters created by the treatment in order to provide a good transmission of energy between two subsequent subphases in the same prints. The settlements induced during the Dynamic Consolidation treatment are an average of 50 percent higher than those induced by the earth-fill load test. A great many pressuremeter tests were performed before, during, and after treatment of both areas. Results showed that the treatment on area B was more successful. The improvement in terms of pressuremeter results is shown on Figure 5, where it is also compared with the original characteris-

Figure 4. Settlements measured under earth fill.

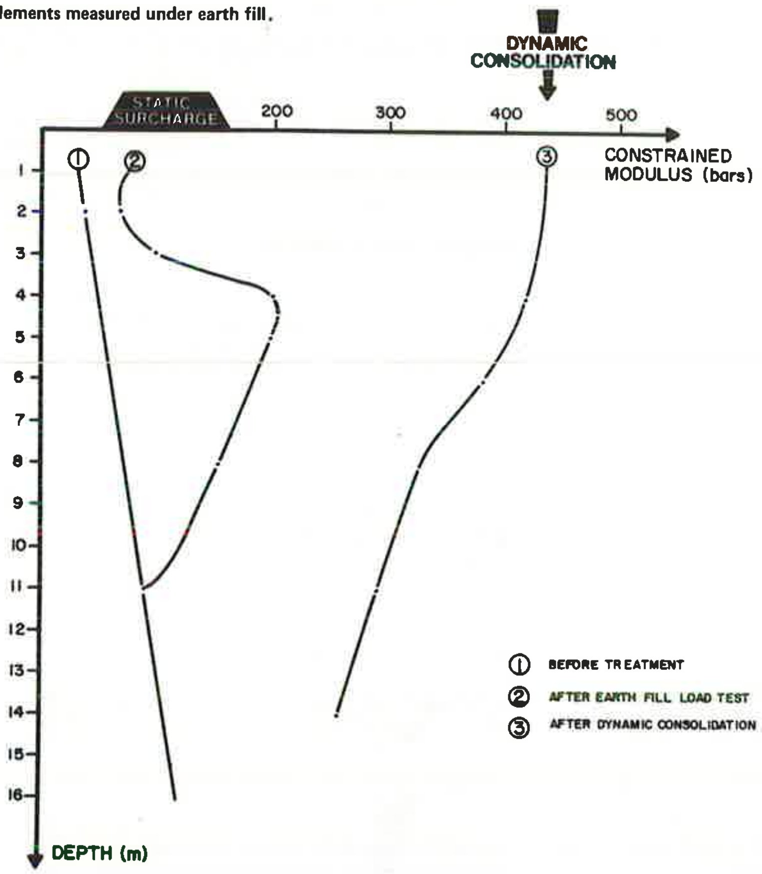
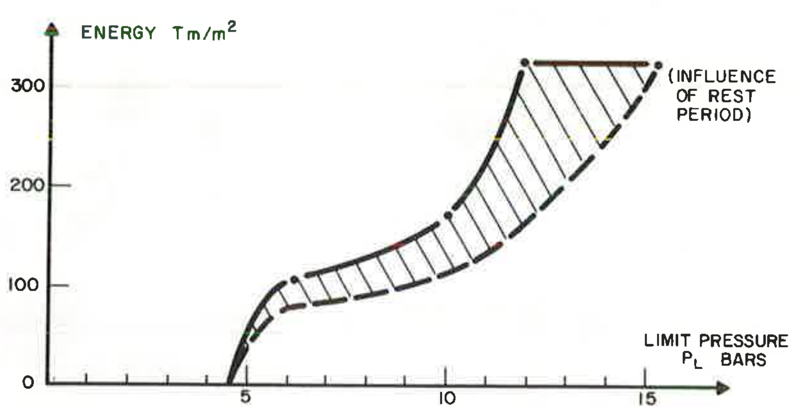


Figure 5. Energy-limit pressure relation.



tics of the soil and those after the load test. The observation of the limit pressures shows three different zones in the treated ground:

1. From 0-30 ft (9 m) very high densification with average limit pressures in excess of 16 tons/ft² (1.6 MPa)
2. From 30-37 ft (11 m) slightly lower results with average around 10.5 tons/ft² (1.0 MPa), and
3. Below the water table 37 ft (11 m) down, a regain of the characteristics with limit pressure around 15 tons/ft² (1.5 MPa).

Tests immediately after treatment and two weeks after treatment showed that the characteristics are improving with time (Figure 5). This is explained by the very fine composition of this material and, therefore, the time required for the water pressure to dissipate.

The analysis of results obtained after treatment enabled the determination of the parameters that govern the relation between energy and depth. The equation used is

$$H = cd\sqrt{E} \quad (1)$$

where

- H = depth of influence of the treatment (m);
- c = coefficient depending on soil conditions;
- d = coefficient determined as follows, for free drop d = 1 or for crane drop d = 0.9; and
- E = energy per blow (Mg•m).

For the very high densification zones described above, c is 0.6. For the lower densification below that zone, c is 1.

By using all these parameters, a 40-ton pounder can be calculated to highly densify 60 ft (18 m) and collapse 100 ft (30 m) of mestastable soil. These numbers for a 150-ton pounder would be 107 ft (32 m) and 173 ft (52 m), respectively.

CONCLUSIONS

The extensive efforts that were put into the design, treatment, and control of this test section have largely improved the knowledge and understanding of the behavior of mine spoils. The pressuremeter tests were found to be a reliable and practical method of evaluating the engineering characteristics of this material, which are usually difficult to assess due to their heterogeneities.

The Dynamic Consolidation treatment improved this very fine and heterogeneous material dramatically. Depending on the type of construction and depth of the mine spoil, different machines with different energies per drop can be used. Densification of soils 30- to 100-ft deep can be achieved. Postconstruction total and different settlements are largely reduced to tolerable levels.

A Dynamic Consolidation treatment on mine spoils can be successfully completed for a fraction of the cost of other conventional techniques, such as over-excavation and backfill or piles.

Wick Drains, Membrane Reinforcement, and Lightweight Fill for Embankment Construction at Dumbarton

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The use of special features to permit embankment construction over soft bay mud is reported. These features included reinforcing fabric, lightweight fill (sawdust), and vertical wick drains, a system that allows construction to proceed on schedule without major foundation failures. An instrumented test embankment that incorporates these features was constructed by the California Department of Transportation (Caltrans) in 1979 at the bridge head of the east approach to the new Dumbarton Bridge. The successful performance of the test embankment provided data for developing specifications for construction of the 2.4-mile embankment contract across the soft bay mud deposits. The fabric provided initial support over the bay mud, lightweight fill reduced loading to ensure ultimate stability, and vertical wick drains accelerated foundation consolidation, which allowed up to 7 ft of settlement to occur in 1 year as opposed to about 50 years under the same loading with normal drainage conditions. Polyvinyl chloride (PVC) wick drains were found to be 40-50 percent as efficient as Alidrains in accelerating consolidation. Their efficiency increased with greater hydrostatic pressures. Instrumentation monitored and controlled the rate of embankment placement. These special features were successful in maintaining stability during construction that would not have been possible by the use of conventional construction techniques.

Embankment placement over soft compressible foundation soils has caused many perplexing problems for the transportation engineer, both during construction and in long-term pavement maintenance. The selection of a particular foundation treatment to aid construction and reduce future maintenance depends on the extent and character of the soft foundation deposits. (i.e., Can they be removed and replaced with more competent material or improved by consolidation and resultant strength increase?)

The soft muds in the San Francisco Bay area have presented a challenge to California Department of Transportation (Caltrans) engineers on a number of occasions. The most recent challenge is the embankment construction for the approaches to the new Dumbarton Bridge. The existing low-level lift span bridge carries traffic for CA-84 across the southern portion of San Francisco Bay between Alameda and San Mateo Counties, in Caltrans district 4. The new 1.6-mile long, high-level bridge structure, which is under construction, should be open to traffic through detour connections in 1982. The approach embankments to this facility are also under construction. The east approach embankment extends from the bridgehead across the Newark salt ponds to Thornton Avenue, a distance of 2.4 miles. The west approach embankment construction covers a distance of 1.6 miles (Figure 1).

This paper discusses the construction and performance of a test fill, the east approach embankment construction, and the development of specifications for special features in embankment construction used