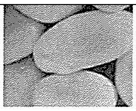


Densification Equipment Design Principles

As the designer of the vibro-draining equipment, the author is prepared to accept the hypothesis and act accordingly. The current equipment design will therefore be reviewed, and revised where necessary to optimally treat saturated masses of silt or sand size which are loose. The objective will be to arrange the grains into a structure where they are oriented with their longer axes mutually parallel and horizontal, and in tight mutual body (as opposed to point/asperity) contact. A packing arrangement of this configuration will not only remove the possibility of liquefaction failure but will also avoid strain softening and provide a stiff and dilative response to loading. The route towards this goal will be an approach using the three criteria applied earlier in considering earthquake liquefaction: how to get the energy to the required depth; what type of energy to use; and, how to manage the water.

REACHING TO DEPTH

Since densification may, as a first stage, involve precipitating collapse of liquefiable ground, the densification energy must be controlled in such a manner as to avoid regional failure. This normally requires that the mass be treated a little at a time, not all at once. One common method, and the one used in vibro-draining, is to insert into the ground an energy source (stinger) attached to sufficient extension rods to reach the required depth. The stinger is then activated and withdrawn either at a predetermined rate, or on the basis of ground/water response monitoring. This procedure is repeated on a preselected triangular array spacing which is appropriate for that particular material.

COMPACTION ENERGY

Efforts to densify non-cohesive soils almost invariably use vibrations of one sort or another. One might wonder why, if liquefaction and strain softening can be brought about by purely monotonic loading, is it not equally reasonable to expect the simple application of monotonic force to achieve densification in the same soil types. In other words, why will pretreatment by static pressures not stabilize materials against subsequent static pressure changes of lesser magnitude. Why the need to call upon a treatment in the dynamic mode? The reason is that since the mass contains innumerable particles, each with several points of interference with its neighbours, reshuffling into a tighter packing cannot be achieved in a single move. During any one episode of mass deformation particles will attempt to move to where they can best resist the motion. The preferred location and orientation of the particle will depend on where its neighbours moved to in the last round of loading. Because the movement of one particle creates a new opportunity for another particle a sequential chain of consequences is generated. Thus it takes many repetitions of mass deformation to give the multitude of particles the opportunities to achieve optimal density of packing.

Ideally, since particle movements necessitate pore water displacements, the repeated mass deformations required to produce stiffer soil response should be applied slowly enough to permit the water to evacuate the vicinity where void space is diminishing. Given the time and economic constraints which exist in all engineering work this ideal is practically impossible, so some compromise position must be sought. It is only by setting aside concerns about accommodating pore water migration that the rate at which the deformations are enacted ceases to be a mechanistic constraint on densification equipment. This concession opens the door to vibratory loading, and the many methods and devices which utilize this simple and highly adaptable loading mechanism. As a consequence, the use of vibrations has become the method of choice in densifying non-cohesive masses, and this is irrespective of whether or not they are water saturated.

WATER MANAGEMENT

Incorporating the pumped filter/drain module into the system was a direct effort at water management within the mass while the vibrator was working, that is, concurrently with compaction. This module serves three functions:

- it minimizes the period during which the mass is in temporary suspension;
- it imposes a lateral seepage flow towards the stinger which encourages particles to approach the energy source;
- it compensates somewhat for the practical compromise of introducing high frequency vibratory energy into a saturated mass.

To put the value of the filter/drain module into some perspective, its influence may be approximated to having a filtered conduit exposed to atmospheric pressure adjacent to the zone being densified. In this context it is important not to overrate the ability of seepage flow to force translation of grains. The fact is that once a particle falls out of suspension and is buried beneath other particles it cannot be moved by seepage flow. It is only the topmost grain on the surface which can be moved, and even that requires a lateral hydraulic gradient of about 0.5. Therefore, it is best to influence a particle before it settles into the mass, while there is still enough space around it to let higher than normal mass velocities envelope it. Consequently, it is essential that drainage be as close to the vibratory energy source as can be arranged, and for it to pump water out of the mass while the mass is still slurried.

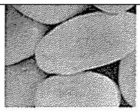
OPTIMIZATION INDICATED

Working in the very fine materials at Myra Falls gave rise to freezing in the filter/drain module. This restriction of water channels exacerbated the situation by further reducing the heat transfer normally available from the seepage flow. The consequent diminishment of the effectiveness of this critical element needs to be rectified.

Currently, the filter/drain module sits above the vibrator. Since the optimum orientation of particles is long-axis horizontal, the indication is that the drain should be made to surround the vibrator. This modification would create seepage flow which was predominantly horizontal and thereby promote the most favourable particle orientation.

Finite element analyses of steady state seepage flow into the Vibro-Drain indicate that the filter/drain module produces horizontal gradients in excess of 0.5 within a radius of 2 m at surface level. This radius of influence increases to over 5 m at a submergence of 30 m. Since array spacing does not normally exceed 3 m (11/2m radius) it is considered likely that the current dimensions of the Vibro-Drain modules can be reduced, possibly leading to a significant miniaturization of the equipment.

Despite the encouraging indications emphasised here it is necessary to keep in mind that there are many approaches to densification, some being more appropriate than others in particular cases. There is no one tool that can do all jobs. Use of the Vibro-Drain will therefore be restricted to what it is designed for, and that is, saturated deposits of loose non-cohesive materials, predominantly in the coarse sand to fine silt size range.



Summary and Conclusions

SUMMARY

The Vibro-Drain approach to ground improvement was successful in the sandfill of the Molikpaq for which it was designed.

Results obtained in the silt sized tailings at Blackdome gold mine realized the possibility of densifying silt deposits.

Field trials in the interlayered tailings at Myra Falls which were predominantly in the clayey silt size range yielded surprisingly encouraging results.

Difficulty in coming to a clear understanding of what had actually happened at Myra Falls stimulated a search for a fundamental mechanistic hypothesis which could deal with the general topic of load-deformation behaviour of cohesionless masses, as well as the particular topic of how the Vibro-Drain interacted with deposits which were vulnerable to earthquake liquefaction.

The route taken was to examine the various components of the solid phase's geometric attributes. This was done to assess the effects these could have on the geotechnical properties of masses composed of mineral grains, water, and air. Particle size, packing density, mass gradation, and grain shape effects were considered in isolation prior to attempting to formulate an understanding of their composite interaction.

To allow the behaviour of a mass of separate and individual particles to be visualized, the supposition was made that all particles were ellipsoidal. This simplifying assumption then lead, through the application of physical laws to a working hypothesis.

HYPOTHESISED MECHANISMS

The hypothesis deals with three separate aspects of the mechanisms which govern load-deformation behaviour. It suggests the following:

Genesis of Soil Structure

- Particles deposited from streams and rivers are naturally predisposed towards forming a dense structure.
- Small particles deposited in the presence of upward water flow vectors can form loose structures.
- Fine grained deposits formed in a moist environment can accumulate into very loosely aggregated structures especially when the grains are more elongated.

Load-Deformation

- Particles tend to adopt an attitude in which their longest axis becomes normal to the dominant pressure front.
- Asperity breakage is a precursor to the collapse of a cardhouse structure.
- Dense packings, when forced to deform, require energy input in order to dilate.

Generation of Pore Water Pressure

- Excess pore water pressure is generated by relative motion between the water and the particles.
- The magnitude of the excess pore water pressure is dictated by the particle size and the speed of relative motion.
- An upper bound excess pore water pressure value can be calculated for any particle size.
- Negative pore water pressure within a saturated mass is caused by a tendency towards localized water cavitation in the void space.

- Cavitation is induced in dense masses during deformation when the rate of dilation exceeds the rate at which inward seepage can accommodate the volume change.

CONCLUSIONS

Applying the hypothesis to the several issues of interest in treatment of liquefiable ground leads to the following positions:

Liquefaction of Laboratory Specimens

- The phenomenon of liquefaction recorded in the laboratory is confined to specimens constructed in a moist environment.
- During the Steady State "flow" the frictional resistance is only marginally less than the maximum drained value.
- The laboratory indication that resistance to liquefaction failure apparently reduces as confining pressure increases could could be false and related to grain orientation and asperity breakage during the consolidation phase.
- The condition referred to as "cyclic mobility" is an artifact of the procedure and has no counterpart in nature, and little, if any, application in design.

Earthquake Liquefaction

- Earthquake induced liquefaction is simply the collapse of a very loose soil structure into a temporary suspension.
- Liquefaction *flow* can follow structural collapse in situations where there is an externally applied gradient capable of translating the resulting temporary suspension.
- Rayleigh surface waves are more likely the triggering event in earthquake liquefaction than are Shear body waves.
- The post-liquefaction condition of a mass which was induced to collapse under a short sequence of surface waves could be left in a vulnerable state.
- Sand boils and water eruptions are confined to areas of local weakness in the vadose zone or other impervious surface layer.

Deposits Vulnerable to Liquefaction

- Silt and sand sizes can sustain the excess pore water pressure necessary to keep a deposit in temporary suspension during which time it is capable of flowing under an external gradient.
- It is not possible to generate significant excess pore water pressure in uniform gravel sizes or larger.
- Only a minor perturbation is necessary to cause a very loose structure to collapse with large deformations and release of energy.
- Densely packed structures do not collapse, but rather dilate with energy input being demanded to allow deformation.
- Uniformly graded masses can contain the large void space necessary for the particle reorientations and movements preceding structural collapse.
- Well graded soils offer mutual kinematic interference to particle rotation and limit the amount of relative movement between the solid and water phases.
- Well graded soils cannot generate high levels of excess pore water pressure during failure.
- Elongated grains are intrinsically more stable than rounded grains provided they are deposited by stream flow.
- Elongated grains deposited in a moist environment are more likely than rounded particles to form a cardhouse structure.
- A good appreciation of the geologic forces at work when the deposit was formed is the priority requirement in site assessment.
- Earthquake liquefaction is limited to uniformly graded water saturated masses of non-plastic materials which are in the sand and silt size range and which were deposited in a manner which promoted the formation of a cardhouse structure.
- Stream and river deposition should produce denser packing than lake sedimentation.
- Natural soils, either deposited in channels where the geometry

gave rise to upward stream flow vectors, or aeolian soils formed in a moist environment, are potentially vulnerable.

- Earthfills such as dredgate and tailings, when either the slurry concentration was too thick to permit particles to settle out independently, or the discharge velocity created upward currents, are potentially vulnerable.

Myra Falls Interpretation Solution

- The improvement in deformation behaviour of the silt/sand/clay tailings at Myra Falls was a result of breaking down a cardhouse structure and causing the grains to adopt a more horizontal orientation.
- The shortfall in water discharge from the filter/drain module is attributable to two causes:
  - (a) restriction in drain conduits due to icing resulting from air expansion heat losses at the air-motor discharge; and
  - (b) seepage flow to the under-drainage blanket in response to a substantial downward site gradient.
- The treatment was successful in making the silt/sand/clay tailings safe against earthquake liquefaction failure.

Assessment and Modification of the Vibro-Drain

- The original belief, in both the Vibro-Drain concept and its Island Building predecessor, that it was best to try to influence grains while they were still in suspension, and as yet unburdened was correct.
- For optimal densification of liquefiable deposits, vibration accompanied by some manner of water management, is indicated.
- The intake element of the filter/drain module should surround the vibrator element.
- Freezing of exhaust water during low level discharges must be rectified.
- The active elements of the system can be selectively miniaturized.

Glossary

The following is a definition of terms in the senses in which they have been employed in this text:

asperity:
an irregularity in the shape of a particle consisting of a local protrusion above the general surface

cardhouse structure:
a loose assemblage of discrete particles in which the structure lacks redundancy and is formed of randomly oriented grains where inter-particle support is carried mainly at point or asperity contacts

excess pore water pressure *(epwp)*:
pressure in excess of hydrostatic caused by relative movement between the phases

hydrostatic pressure:
the pressure at any point in open water at rest (no flow)

hydraulic gradient:
rate of change of ***epwp*** or ***npwp*** in a particular direction

liquefaction flow:
translation of mass under influence of external lateral hydraulic gradient while mass is in a state of temporary suspension

negative pore water pressure *(npwp)*:
sub-atmospheric pressure caused by cavitation somewhere within the mass

piezometric head:
the height water could rise in a standpipe at that point

quicking:
solid phase held in suspension by external upward gradient following retrogressive erosion of mass

slurry:
solid phase kept in temporary suspension by turbulent flow

stoping:
upward translation of a front where the mass above is being undermined by the mass below adopting a higher density

suspension:
solid phase at rest in liquid phase (eg. muskeg)

temporary suspension:
solid phase supported on a water buffer while the voids are venting at a rate dependent on k and i

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