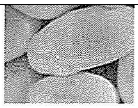


Interpretation Problem

The Myra Falls' results, while encouraging from an empirical standpoint, created a problem in interpretation because they cannot be entirely explained within the framework of the pre-existing concept of how vibro-draining changes the ground. The problem is that, based on visual observation in the field, the author believes not enough water was discharged from the drainage system to fully account for the size of the depression observed at ground surface. The total discharge should be equal in volume to the amount of seepage water attracted into the filter/drain module, plus, the loss in void space within the zone of densified tailings. While there is little doubt, in such fine grained tailings, that sufficient water circulated through the system at Myra Falls to satisfy the requirements of seepage force generation, it cannot be concluded that the discharge was sufficient to account for the surplus pore water from the collapsing voids. The question then is, if that water did not vent through the discharge system, where did it go?

Venting water vertically in a horizontally stratified deposit is possibly limited to the interface of the extension pipes. It is more reasonable to look at horizontal dissipation through the occasional coarser sand seams within the tailings. The scenario which would fit least comfortably with the preconceptions of vibro-draining mechanics is that the water vented horizontally away from the stinger. This idea would have water concurrently travelling radially in opposite directions at roughly the same level, which although not impossible with differential horizontal hydraulic conductivities at close vertical intervals, is difficult to utilize as a working model. It is also possible that there was a watershed at some radial distance from the stinger, within which distance water migrated towards the filter/drain module, and beyond which, water vented to the surrounding tailings.

The importance of clarifying this situation is that if the improvement made in the behaviour of the tailing at Myra Falls was not associated with the control of pore water movements, then perhaps the same results could have been achieved using a standard Vibroflot, or similar device, with the benefits being attributed simply to mixing of the interlayered deposit. An improvement in overall gradation results when two or more uniform gradations are mixed, and provided the excess pore water has time to drain before loading, the engineering behaviour of the composite would be expected to be more competent. But mixing does not appear to have been the source of the benefits at Myra Falls since the post-treatment CPT traces indicate pronounced layering similar to the initial condition, implying the layers remained substantially intact. This observation therefore suggests that within the many interlayers the grains were forced into a denser packing, and the enhanced behaviour was not simply a matter of improved gradation. So, it is necessary to look elsewhere for an answer.

Up to this point the Vibro-Drain equipment design had been based mainly on ideas related to seepage forces. The results achieved in the Molikpaq showed that vibro-draining worked well in clean uniform sands, with sufficient water discharge to account for the improvement within the framework of the seepage force concept alone. But now Myra Falls raised some doubts. It was decided, therefore, that in order to be able to determine the utility limits of vibro-draining, without incurring excessive field trial costs, to proceed as follows:

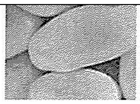
- Take a fresh look at the physical implications to saturated mass behavour of differences in particle size, packing density, gradation, and particle shape, with emphasis on particle interaction with moving water.
- Think through the mechanics of how discrete particles develop into particular mass arrangements, that is, the genesis of soil structure.

- Try to develop a conceptual model governing the behaviour of saturated masses of discrete particles when those masses are subjected to deformation.
- Attempt to achieve a clear hydrodynamic understanding of the generation of both excess positive, as well as negative, pore water pressure.
- State clearly what reality is being invoked by the word *liquefaction*, because the best solution cannot be designed if there is vagueness about the problem to be treated.
- Test any resulting hypothesis against published laboratory results to see if it might be compatible with the measured load-deformation behaviour of saturated sand specimens.

If a credible working hypothesis can be developed in this way, employ it to see if it can shed any light on the following:

- Evaluating earthquake liquefaction potential in the field, and indicate what level of density is actually necessary to withstand liquefaction at a particular site.
- Discriminating between ground types (geology) which need to be densified, from those which are naturally secure.
- Interpreting the Myra Falls results with sufficient confidence to allow an opinion to be rendered on the adequacy of the treatment at that site.

Following such an approach to a better understanding of load-deformation and pore water pressure generation, and of what level of compaction is necessary in a particular soil type to resist earthquake liquefaction, it was hoped that more effective progress could be made on the optimization of the Vibro-Drain equipment to treat only those soil types needing treatment.



Effects of Solid Phase Geometry on Behaviour

Natural soils, earthfills, and even mine tailings, contain such a range of individual particle shapes and sizes that the only practical way to attempt to understand the mass behaviour of these deposits is by empirical means, that is, from experience or by testing. Nevertheless, some useful insight into the viable range of properties of cohesionless deposits can be gained from consideration of simple geometry and fluid mechanics. In a similar way, as will be shown subsequently, thinking in terms of physics and kinematics can help put reasonable boundaries on the concepts of liquefaction and densification. Four aspects of particulate masses will now be considered: particle size, packing density, mass gradation, and grain shape.

PARTICLE SIZE

A conceptual, as opposed to an empirical, evaluation of the effect which particle size has on the engineering behaviour of a saturated mass composed of discrete solid grains is not possible without simplifying the system a great deal. Assuming all particles are spherical and of equal size is a good starting point.

Table 3 lists some physical attributes for three particle sizes with particular emphasis on those attributes which have a bearing on relative motion between the solid particles and the pore water. The numerical values are for spherical solids of Specific Gravity ("G") equal to 2.65. The spherical diameters chosen are 10 mm, 0.3 mm, and 0.01 mm. These diameters are the mid-range points on a logarithmic grain size plot for Gravel, Sand, and Silt, respectively. This is the only justification for listing the values under a "Soil Type" headings in the tabulation. It is perhaps worth recalling that, in the laboratory, for "size" we rely on sieve and hydrometer analyses, both of which only approximate the second largest particle dimension.

A ballpark figure is given for the number of particles of each size required to make up one cubic centimetre of an aggregation at 50% relative density. Since it takes a million ccs to make a cubic metre, then, especially in fine sands or silts, there is obviously no way of dealing with soil structures other than statistically. Even in the laboratory, determining the size and shape of each particle in a small specimen cannot be attempted. Sometimes for shape micro-photographs are taken before testing, but the same grains cannot be found after testing to see if, and to what extent, the test changed them. This point is relied on later to justify approaching an understanding of mass behaviour in terms of average, or typical shape, rather than specific particle shapes.

Attribute	**Units**	**"Soil Type"**		
		SILT	**SAND**	**GRAVEL**
Particle Diameter	mm	0.01	0.3	10
Number per Unit Volume	#/cm³	billion	40,000	1
Sedimentation Energy	joule	$2*10^{-19}$	$5*10^{-12}$	$2*10^{-4}$
Suction Head (mc=5%)	m H_2O	360	2.2	0.04
Terminal Velocity	mm/s	0.07	35	750
Hydraulic Conductivity	m/s	10^{-6}	10^{-3}	$10^{\pm 0}$
Surface to Volume Ratio	1/mm	150	5	0.15

Table 3. Effect of size on physical attributes of spherical particles

Sedimentation Energy is an estimate of the kinetic energy of a particle as it comes out of suspension in the transporting stream. The values shown were calculated from the buoyant weight of the sphere and the stream velocity at which such a particle would exist on the Hjulström transportation/sedimentation boundary. This gives some idea of the degree to which the newly arriving particle would impact other particles already lying on the stream bed.

Suction Head is the negative pore water pressure associated with the inter-particle menisci in partially saturated soils. The values shown were calculated for a moisture content of 5% using the relationship developed in Hodge (1963). This is some measure of the effect of partial saturation on soil structure development in cases where the deposit is formed subaerially from an accumulation of moist particles.

Terminal Velocity is the rate of free fall of a discrete particle through water. These values were calculated using standard fluid mechanics. Apart from being in itself an important parameter, it is also useful as a measure of the relationship between particle size and the opposing forces of viscous drag and gravity. The lower values indicate that drag is more dominant.

Hydraulic Conductivity was calculated using the Hazen (1935) approximation. Since ***k*** controls the rate at which water can move through a stable structure, it therefore dictates the time frames for liquefaction movements and densification efforts in water-saturated masses.

The Surface to Volume ratio is primarily used as an indicator of physio-chemical activity. Higher ratios show that large areas of the particle surface are available for cation exchange and adsorbed water, thereby highlighting the likelihood of cohesion between particles. This ratio is also helpful when trying to appreciate to what degree moving water hinders or helps liquefaction or densification since drag forces are surface related and friction is volume related.

The values in Table 3 show the degree to which particle size can influence the forces which govern soil mass behaviour. On any of these counts it is readily apparent that there is an immense difference between sand, gravel, and silt sizes. It therefore seems apparent that any assumption or opinion which might place sand and gravel or silt in the same category with regard to liquefaction potential, or to think these very different deposits would respond in the same way to normal densification efforts and approaches, would be quite unreasonable.

PACKING DENSITY

The loosest possible arrangement of single sized spheres is when the locus of their centres form the edges of a cube. This packing has a void ratio of 0.91, and each particle makes contact with six neighbours. This loose structure is in a precipitous state of stability, only requiring a minor perturbation to cause it to collapse.

The simplest collapse mechanism is for the particles of one layer to move into the troughs of the underlying layer, a translation of 0.71 times the spherical diameter at 45°. The resulting arrangement is the densest possible, and has a void ratio of 0.35, and each particle makes contact with twelve of its neighbours. Because the particles lose elevation, this contraction in volume is accompanied by a 29% loss of potential energy.

	Density and Gradation	e	mc%	s:w	U_c	#i-pc	Shear Behaviour
A	Loose	0.91	34	1.1	1.0	6	contractive
B	Intermediate	0.65	25	1.5	1.0	8	contractive
C	Dense	0.35	13	2.9	1.0	12	dilative
D	Idealized	0.37	14	2.7	1.3	14	dilative
E	Loose, loose matrix	0.29	11	3.4	≥ 2.7	≥12	contractive
F	Loose, dense matrix	0.14	5	7.1	≥ 2.9	≥15	dilative

Table 4. Features of some idealized packing arrangements and primitive gradations for spherical particles

If the newly formed dense arrangement is sheared it will not dilate to the original void ratio of 0.91, but to an intermediate void ratio of 0.65, accompanied by an energy demand of 16%. This intermediate packing, where each particle makes eight contacts with neighbours, is in a saddle state of instability, needing only a nudge to fall back into the densest packing arrangement and give up the 16% energy again.

Shear cycles subsequent to the initial collapse from the loosest packing result in reversible volume changes, with void ratios altering between 0.35 and 0.65, accompanied by potential energy gains and losses of 16%, depending on contraction or dilation. This reciprocation between void ratios as the structure dilates and contracts is essentially a pumping action, with each dilation drawing fluid into the pores, and each contraction driving fluid out of that space again.

Table 4 lists the following for each of these three packing arrangements:

e	void ratio
mc%	moisture content (saturated)
s:w	solid to water ratio
U_C	Uniformity Coefficient
#i-pc	number of inter-particle contacts (array, not matrix).

Whether the structure will contract or dilate under shear deformation is also shown, and here it should be noted that the tabulated values are independent of particle size.

MASS GRADATION

Theoretically, an alternative way of stabilizing the loosest array, one which does not involve a structural collapse, and the large energy release associated with such an event, is to partially fill the void spaces within the loose structure with smaller particles. In other words, improve the gradation by changing it from uniform to non-uniform. The goal is to make it kinematically impossible for the structure to deform without dilating, that is, the array could not shear without energy input. There are several simple (computable) geometric ways of accomplishing this, only two are mentioned here.

The first is referred to here as "idealized" because it is not a practical proposition. It entails introducing slightly smaller (73%) particles into the interstices within the loose structural array. This arrangement provides a kinematically blocked structure which cannot deform without immediate dilation. The second is to fill the voids with a matrix of uniform sized particles which could enter the existing open structure through the spaces between touching spheres (41%). In this case the manner in which the composite mass responds to deformation is dependent on the rate of shearing and the matrix density.

The attributes of the composite mass are listed in Table 4 for the idealize gradation, and for a loose and a dense matrix. What is implied by this tabulation would appear at first sight to contradict intuition since it shows that the contractive arrangement E has **e**=0.29 and U_C=2.7, whereas the dilative arrangement C has **e**=0.35 and U_C=1.0. But, once it is acknowledged that the stability of a loose structure is dictated by the density of the matrix, it becomes apparent that the interpretative value of the data comes from the first four rows. There it may be seen that stability increases with reduced void ratio, increased number of inter-particle contacts, and with some further benefit coming from improved gradation.

A term referred to as the "solid-to-water ratio" has been introduced here in an attempt to facilitate some intuitions about the possible behaviour of a two-phased system in motion. Knowing that the loosest array (A) has almost equal volumes of solids and pore water (**s:w**=1.1) would seem to justify placing it in a very different category from (E), the loose structure filled with a loose matrix, which has 31/2 times more solids than pore water. It is difficult to visualize making the latter soil, composed as it is, predominantly of frictional elements, flow as a heavy fluid simply by applying a shear distortion.

GRAIN SHAPE

As noted earlier the numbers of individual grains in even a small volume of sand or silt are truly astronomical. Consequently, it seems reasonable to attempt to understand mass behaviour in terms of an assemblage of typical particles. The fact that such a particle does not exist is just as valid as the statement that the average person does not exist anywhere as a living human being, nevertheless, this statistical convenience allows some progress to be made in terms of group dynamics. So, for the purposes of this study it will be assumed that the mass is made up entirely of particles of a single geometric shape. It is therefore important that there be some rational basis for adopting one geometric shape over another.

Up until this point the discussion has been limited to perfectly spherical particles. This is because the sphere is the simplest shape to deal with; the sphere being the only geometric shape whose size, volume, surface area, and aspect ratios, or profile in any orientation, can be completely defined and fully described by a single value — its radius or diameter. Despite the usefulness of spherical shapes in assessing the influence of flowing water on particles of different sizes, and for looking into the ramifications of various packing densities and effects of mass gradation on a soil's response to deformation, the conceptual use of spheres can be very misleading if taken too far. The fact is that if particles were truly spherical they could not be heaped up on flat ground to form a mound. In other words, the angle of repose of perfect spheres is zero. Because of its complete symmetry a sphere can be rotated in any direction without the elevation of the centre of gravity changing. Therefore, no work needs to be done to make it roll horizontally on a flat surface, since the rotation does not change the potential of the particle as it moves sideways.

An alternate typical particle shape, if any, should have some relation to the geological forces at play as natural particles evolve during the rock erosion process. In this vein, it appears reasonable to expect that a rather large intact block of fairly homogenous mineralogy would eventually end up as a near-perfect sphere if it was transported far enough. This is because the corners and edges, being more prominent, take the brunt of impacts with other particles during tumbling down slopes and rolling along stream beds, and these projections are gradually flattened by crushing. Thus, the evolutionary tendency for larger sizes (boulders) would appear to be towards a perfect sphere, where all parts of the particle are equally vulnerable or protected. But this simple scenario needs to be modified somewhat to account for the fact that nearly all rock types from which soils originate have some degree of structural anisotropy due to their mode of deposition. This predisposes the block during erosion to asymmetric shape development, and this appears to be more noticeable in gravel sizes than in boulders.

Matters are quite different for particles at the other end of the size spectrum. As the size approaches the dimensions of individually viable mineral crystals it seems reasonable to expect mineralogy to manifest itself in grain shape. This is because for such small particles, see Table 1, the inertia of a moving particle would not be sufficient force in itself to break off significant asperities or fracture the crystal structure. Longer than wide is a characteristic of most mineral crystals, and this suggests a natural tendency towards smaller particles being elongated.

The foregoing generalization, tempered somewhat by empirical observations, implies that while boulder and cobble sizes may be expected to be almost spherical, lack of homogeneity may become increasingly manifest in shape as grain size enters the gravel range, eventually tending towards the ellipsoidal in sands and silts. Perhaps the single geometric entity which could serve to describe the full range of grain sizes would be "egg-shaped", with spheres and ellipsoids, as singular forms of the egg-shape, representing the largest and smallest particles, respectively. Since what is of particular interest here is the particle size range where seepage and gravitational forces are of the same order of magnitude, most of the ensuing discussion will make the simplifying assumption that the shape of all particles is ellipsoidal.

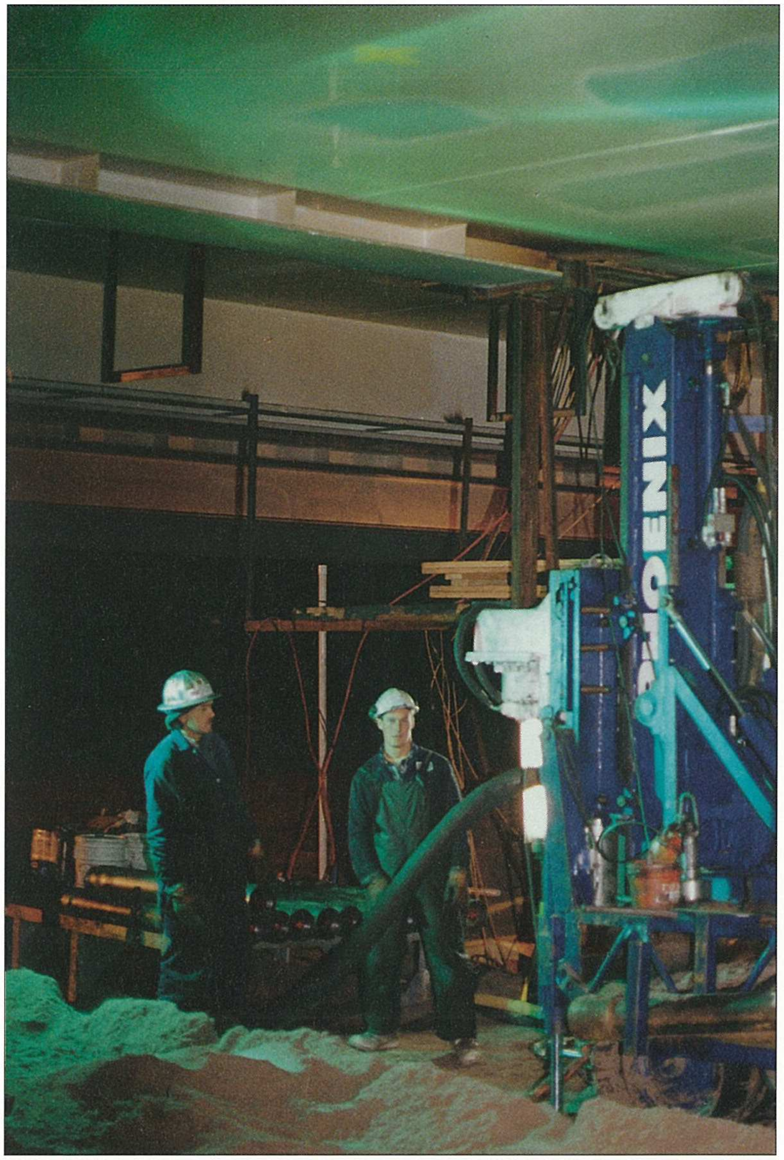
An ellipsoidal shape is one where a particle's length is elliptical and its cross-section is circular. So, like a sphere, an ellipsoid, because of its shape, is inherently unstable in the direction normal to its semimajor axis. But, unlike a sphere, rotating an ellipsoid horizontally in the plane of the elliptical section involves energy. An ellipse has most potential energy when its semimajor axis is vertical, and energy will be released if it is left unsupported. An ellipse has least potential when its maximum radius of curvature is horizonal, and energy, in the form of a force moving its centre of gravity to a higher elevation, is required to make it rotate. Since a particle is most stable when it requires the maximum amount of energy input to rotate it, flat lying elliptical particles are most stable, as is indeed intuitively apparent. The more an elliptical shape departs from that of a sphere, that is, the greater the ratio of the semimajor to semiminor axes lengths, the more a particle will resist rotation in that plane. It can be shown that elliptical shapes having at least a 2:1 axes ratio are required to maintain a 36° angle of repose; unfortunately, the proof of this statement is too tedious to reproduce here.

It is worth noting that what has already been said about void ratio and gradation of spheres is equally applicable to ellipsoids. This is because an ellipse is simply a circle re-mapped in one of its dimensions.

Photograph 1. Vibro-Drain equipment at Blackdome Mine showing filter/drain module (above) and vibrator (below)

Photograph 2

Photograph 2. Molikpaq Platform under ice attack during hydrocarbon exploration drilling in Canadian offshore Arctic
(Photo courtesy of Gulf Canada Resources Inc.)



Photograph 3. Vibro-Drain operating in Molikpaq Core showing deployment under restricted headroom

Photograph 4

Phototograph 4. Vibro-Drain operating in Molikpaq Core showing water discharge from filter/drain module exhaust

Photograph 5. Craters in Blackdome tailings dam u/s slope at locations of two Vibro-Drain treatment axes

Photograph 6

Photograph 6. Myra Falls tailings adhering to Vibro-Drain extension rod after withdrawal from ground

Photograph 7. Vibro-Drain operating at Myra Falls showing water discharge from filter/drain module exhaust

Photograph 8

Photograph 8. Surface settlement and cracking of Myra Falls test pad at location of 7-point treatment array