Hypothesised Mechanisms

Here an attempt is made to generate a general hypothesis dealing with the behaviour of a mass of discrete particles as their loading environment changes. The simplifying assumption will be that the mass may be typified by an assemblage of ellipsoidal solids of uniform size and aspect ratio. The first step will be to see if the application of standard engineering principles to such solids could lead to some expectations regarding the types of soil structures which could be formed under differing modes of deposition. The second step will be to see if by the same approach some insight might be gained into the fundamental reasons for the widely different load-deformation responses portrayed by sands and silts when they are loose, as opposed to when they are dense. The third step will be to introduce water effects so that the influence of relative motion between the solid and fluid phases can be examined.

GENESIS OF SOIL STRUCTURE

For this purpose it is convenient to look into the way in which particles are likely to interact as they are brought together in two widely different environments. The first is the water saturated environment associated with sedimentation on a stream bed. The second is the more complicated case where moist soil is aggregated subaerially.

In the case of fluvially sedimented soil, where the stream flow is laminar, our knowledge of fluid mechanics would lead us to visualize discrete particles behaviour as follows: During transportation the particle will be moving slightly slower than the stream, oriented with its long axis parallel with the flow to minimize drag, and its more blunt end upstream in something of an air-foil attitude. When the steam velocity becomes too slow to hold the particle in suspension the particle will come to rest on the bottom by losing its remaining momentum to the particles already forming the stream bed. Its final attitude will depend on the particular details of its impact, but statistically, this typical particle should end up being oriented with its long axis parallel to the stream flow. This scenario implies a soil structure where there is a natural tendency for particles to have their long axes mutually parallel. In order to accommodate the gravitational field it is necessary that the particle's weight be fully supported by the underlying particles. Therefore, in the vertical axis there is reason to expect good and adequate inter-particle contact. In the stream flow direction, because of the kinetic energy transfer during sedimentation, the newly arrived particle may not itself be in intimate contact with its own generation of sediment, but it will have helped nudge the underlying layer closer together in the stream flow direction. In the third direction, transverse to stream flow, there is no compelling reason for particles to be in contact other than the tendency to seek the lowest potential. This tendency would be more easily satisfied the closer the transverse section of the particle approached circular.

In the case of aeolian deposits it is to be expected that particles coming out of suspension would be randomly oriented, both because wind direction is unconstrained, and drag forces are relatively weak due to air viscosity being so light. In under-saturated masses menisci forming at inter-particle contacts result in surface tension forces existing where particles touch. This influence, quantified as Suction Head in Table 3, depends on moisture content and particles size (Hodge 1963). In such a moist environment, particles arriving at the surface of a deposit can be far more powerfully influenced by negative pore water pressures (suction) than by gravity. Since high suction forces are available at the sharper ends of particles it is possible for a particle to support itself by attaching a pointed end against any available neighbouring surface. This mechanism inhibits the development of intimate vertical contacts between particles since their weight can be carried through a "post-and-beam" type of structure, rather than by bearing on the underlying layer. Consequently, the tendency in this environment is towards forming an open (cardhouse) structure. It is important to realize, given the mechanism whereby discrete particles come to a stable configuration within such a mass, that if this mass subsequently became saturated with water, the suction, which provided an important part of the structural support during aggregation, would be eliminated.

These two routes to soil structure development, one in which particles are deposited from stream flow as a two-phased mass (dense), and the other in which particles are deposited from a turbulent flow as a three-phased mass (loose), now form the basis for deducing the mass behaviour of cohesionless masses at these two extremes of packing density.

LOAD-DEFORMATION

For this purpose, in addition to the assumption that the mass is composed of typical particles of definable geometry, it is also assumed that the grains have surface roughness expressed as asperities which are some small but significant percentage of individual particle size. Furthermore, the idea introduced here is that, in a cohesionless mass, any alteration in the pressure field will require a readjustment of the soil structure to confront it. Since the most stable attitude of a particle is when its long axis faces the dominant pressure, any increase in compression will tend to cause particles to responde by rotating in a manner which will favour having their long axis normal to the direction of the major principal pressure.

In the case of a loose mass, increased pressure will affect the points of contact between grains, this being felt most acutely at the nose of asperities. Some of these promontories will be crushed/sheared with the result that rotation will be facilitated by truncation of that dimension. An overall trend towards preferred parallelism of long axes will result in an improvement in body contact between grains. Where the structural adaption is in response to a vertical pressure increase there will be a reduction in both the potential of the mass and the void ratio. The structure's response to pressure increase beyond this point will depend on constraints to movement in the planes orthogonal to the changing pressure field. If no movement is possible there will be no further structural modification. If movement can take place, the structural deformation will be governed by shear, where the shear stiffness will be determined by inter-particle friction as grains move over grains.

In a dense mass, inter-particle contacts are more substantial and less reliant on asperity interference. Dilation of a closely packed structure during deformation is necessary when push comes to shove. This bulking indicates that what is going on is not a matter of shear failure through the body of grains, but rather intact (save for some asperity wear) grains riding over other intact grains. The increased mass volume also provides some room for grain rotation, and perhaps, a limited amount of rolling where the particle cross-section is circular.

The behaviour of the solid phase outline here is believed to hold true whether the mass is saturated by air or by water, provided that is, that the water is not flowing within the mass. Hydrostatic water does not alter the kinematics of a system, that is, the way in which the soil skeleton adapts itself to a changing force field. Also, it is known that immersion makes no measurable difference to inter-particle friction. But when there is relative movement between the water and the structure, then it is an entirely different matter.

GENERATION OF PORE WATER PRESSURE

The ensuing reasoning adopts the following statements, some of which are axiomatic, as fundamental to an understanding of soil pore water pressure:

- Water can only move within a saturated mass in response to a hydraulic gradient.
- A piezometric head difference within the mass is necessary for a hydraulic gradient to exist.
- For water to flow in a saturated mass there must be a source and a sink available to support the quantity transfer.
- When the water is not moving there is no hydraulic gradient.
- In the absence of flow, the magnitude of the piezometric head has no effect on the soil structure or on individual particles.

Excess Pore Water Pressure

The position taken here is that excess pore water pressure ***("epwp")*** is generated in only one of two ways: (a) either externally because of an inclined phreatic surface, such as is associated with sloping topography, wave loading, or impounded reservoirs, or (b) internally, by relative motion between the solid and water phases. The externally imposed condition is a site specific matter and will be discussed later with respect to liquefaction flow; the internal generation of excess pore water pressure is dealt with next.

When a discrete particle falls through open water it accelerates to reach its Terminal Velocity (V_T) and thereafter falls at that constant rate. While falling at V_T the resultant hydraulic drag force (F_D) against the particle is equal and opposite to the buoyant weight of the particle.

$$F_D = C_D.\rho.A.V^2/2$$

where:

C_D	is the drag coefficient which is empirically determined as a function of Reynold's Number (R_E=V.D/υ)
ρ	is fluid density
A	is a characteristic area normal to flow
V	is the relative velocity
υ	is the kinematic viscosity

This drag force must in turn rely on a pressure front ahead of the particle to sustain itself. An important fact to recognize is that immediately after the particle starts to fall its velocity is negligible, and so therefore must be the drag force and the pressure front. At this stage the particle is in fact close to weightless because it is accelerating, essentially unimpeded, in the gravitational field. Consequently, the water is not pressurized at the beginning of the fall, and pressure builds up only gradually as the fall speeds up. Complete transfer of the particle's buoyant weight to the water is fully realized only after the speed of the particle's fall reaches V_T. This time-dependent weight transfer was observed in simple experiments where particles of various shapes and weights were dropped through a column of water while noting when the full buoyant weight was registered in the container.

Larger particles such as gravel take a great deal longer to reach V_T than do smaller particles such as silt. To emphasize this point, Figure 12 was made for the range of sizes of interest here, and for the specific case of a particle falling a distance of 0.29 times its diameter. This specific ratio of fall distance ("f") to particle diameter ("D") was chosen for illustration purposes since $f/D = 0.29$ is the maximum contraction possible for a two-layer array of spheres or ellipsoids when changing from the loosest (**e**=0.91) to the densest (**e**=0.35) packing. The values shown are for spherical particles since C_D values are readily available, and any inferences will be on the conservative side compared with ellipsoids. Here it is evident that in the silt to fine sand size range a particle fall, or array contraction, of 29% would allow 100% weight transfer from the solid to the liquid phase, while less than 20% of weigh transfer would be accomplished in gravels.

Figure 13 shows the relationship between particle size and distance required to reach V_T, that is, the point of full (100%) weight transfer to the water. For conciseness the ratio f/D has been used to measure fall. Also shown is the fall required to achieve 25%, 50%, and 75% weight transfer. It is now suggested that, with some modification, the data shown in Figure 13 for single particles falling through open water, can provide some upper bound quantification for ***epwp*** generation during the collapse of a loose soil structure, and perhaps, contribute to the general topic of relative motion between the phases within a water saturated soil mass.

After collapse of a loose structure by a jolt/disturbance, the particles fall downwards through the water under the influence of gravity, and on average, the relative motion is confined to the vertical. The hydrodynamics of this situation differs from the case of a single particle free-falling in at least two significant ways: (a) there is interference between the particles; and, (b) the water, as well as the particles, is moving. Since particle interference will retard particle velocities, and thus reduce weight transfer, the first difference may be safely ignored for the purposes of achieving a first approximation to water pressure generation during collapse. This is not so with the second difference.

In a collapsing array the particles move into voids to occupy that space during the process of achieving a denser packing. The water

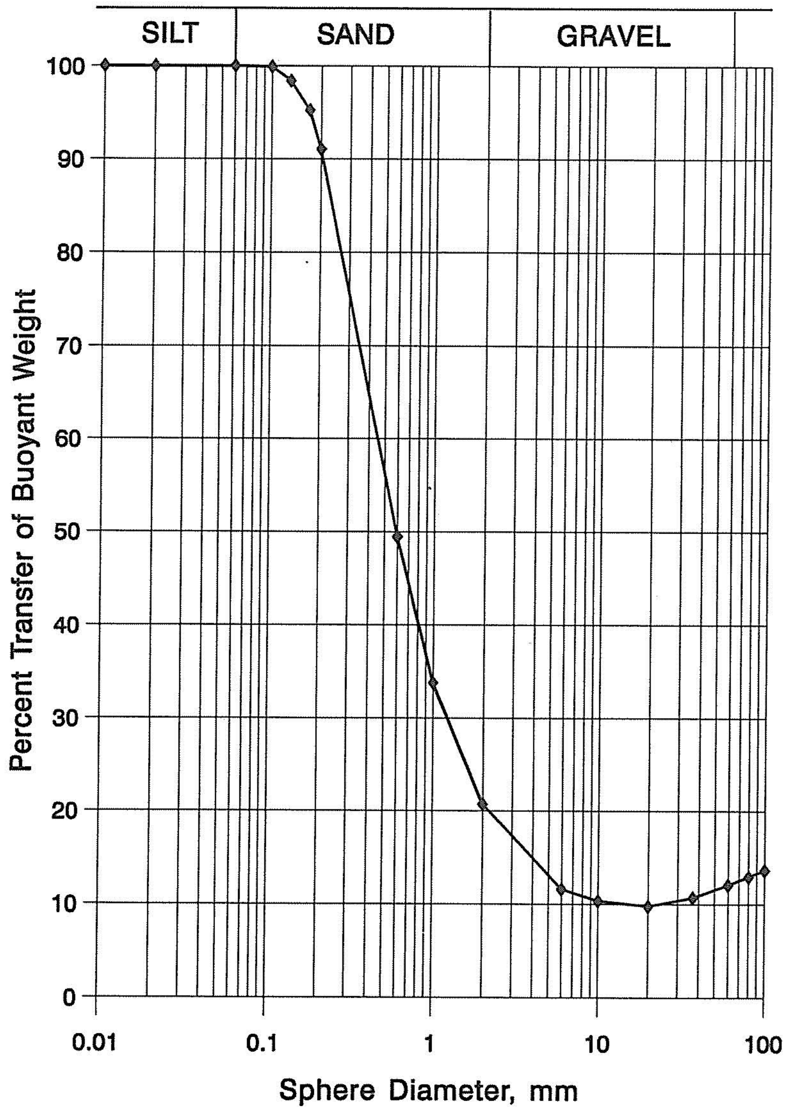


Figure 12. Solid Weight Transfer to Water @ f = 0.29D

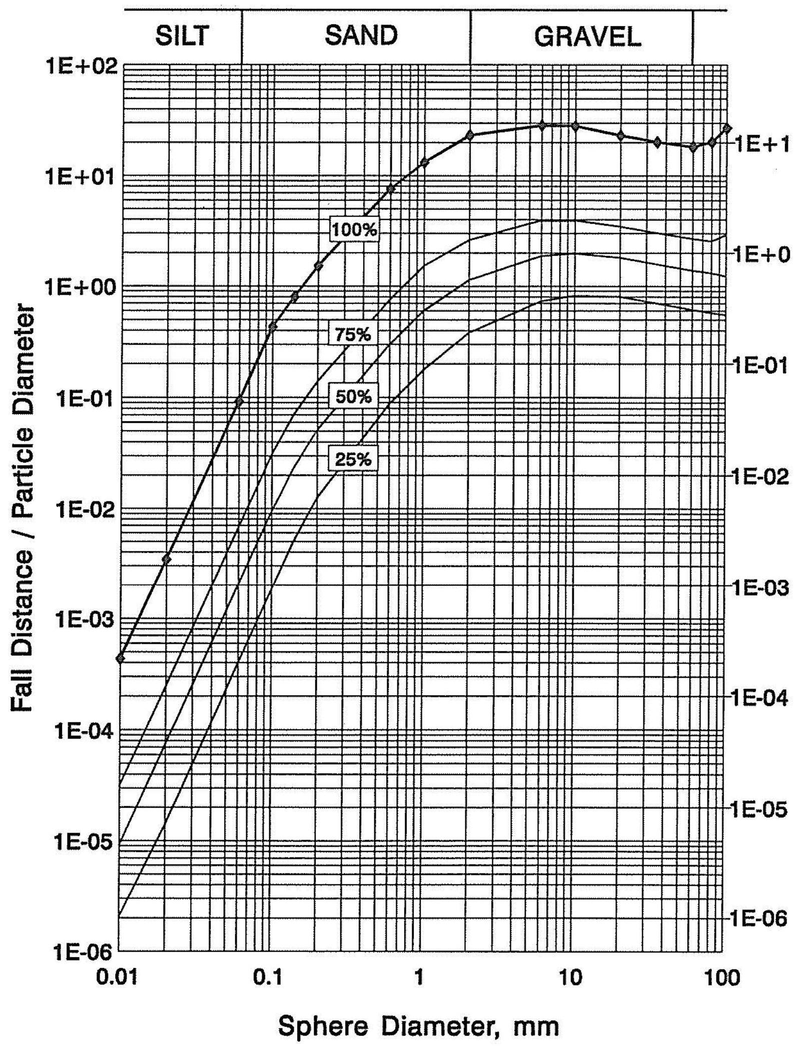


Figure 13. Required Fall for Weight Transfer to Water

must exit the void space at the same rate the particle is entering. Therefore, overall, the upward velocity of the water must equal the downward velocity of the particles. Consequently, the relative velocity between the particle and the water is double the particle fall speed. So, in the case of particle fall within a soil mass, V_T is achieved in half the distance it would be achieved in open water, where the water is only displaced to the side. To ignore this difference would be an error on the unsafe side since lower water pressure generation would be implied. The ordinate in Figure 13 must therefore be halved in order to permit its adoption as an indicator of pressure generation in the water phase. The scale values shown on the right side of the plot are adjusted accordingly.

The maximum pressure which can be generated by each particle in the mass is equal to its buoyant weight, and this is possible only if, and when, it reaches its V_T. The extreme upper bound may be reached in the idealized instance of a collapsing homogeneous array of uniform particle size where all particles could conceivably achieve V_T simultaneously. In this limiting scenario, when the mass of particles had reached V_T, the excess pressure in the water at any depth (z) would equal the buoyant weight of the solid phase above that depth, that is, $\boldsymbol{epwp}=\gamma \boldsymbol{w}.z.(G-1)/(1+e)$. If this were to happen, a vertical upward gradient of $\boldsymbol{i}_{MAX}=(G-1)/(1+e)$ would exist throughout the mass. Figure 13 may therefore be read (using the right hand scale) as the distance particles of a particular size must be able to fall in order for the mass to experience $\boldsymbol{i}_{MAX}$, or some percentage of it. Used in this manner Figure 13 suggests that the upper bound ***epwp*** can be generated in coarse silt when the fall distance is less than 0.1 times the particle diameter, whereas gravel would have to fall up to 15 times its diameter to achieve the same condition. Sands naturally fall between these two extremes, with very much greater relative motion being needed to generate significant ***epwp*** as the coarseness of the sand increases

In Figure 14 the ratio of Terminal Velocity to Hydraulic Conductivity ($V_T/\boldsymbol{k}$) is plotted against particle size. For convenience, ***k*** was approximated with the same Hazen relationship as was used for Table 3. The utility of this plot may be understood by considering the condition depicted by $V_T/\boldsymbol{k} = 1$, where the curve intersects D=8 mm.

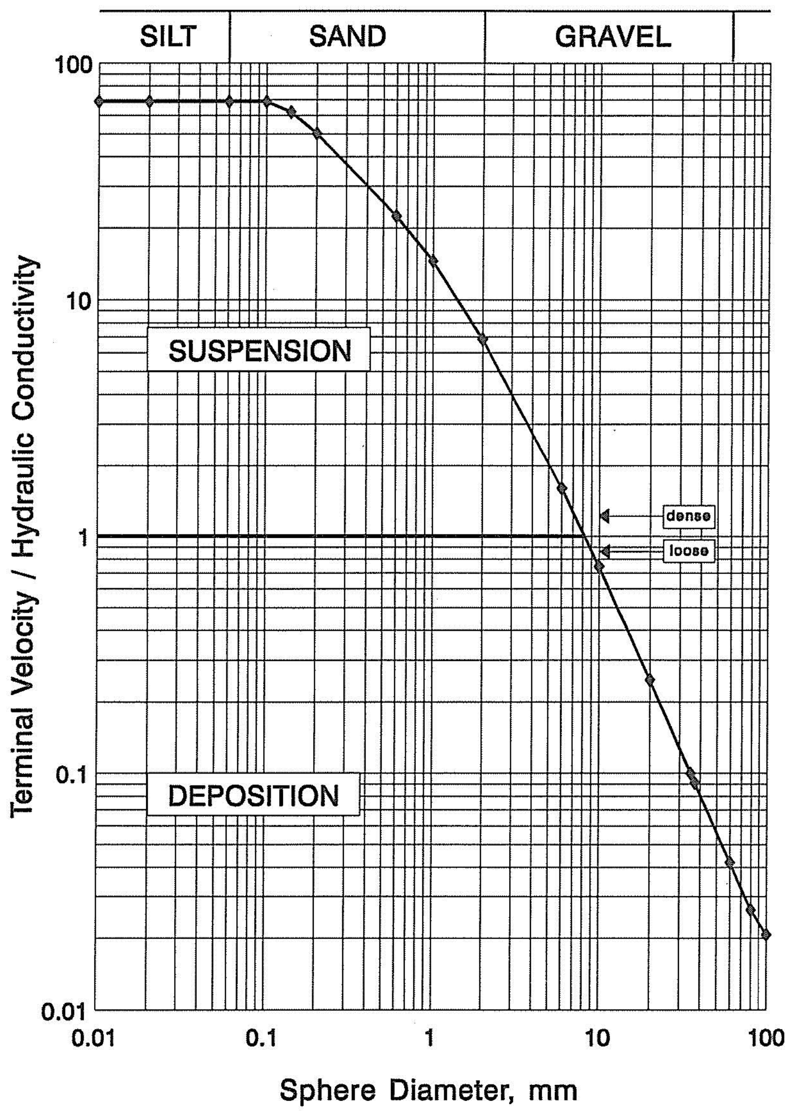
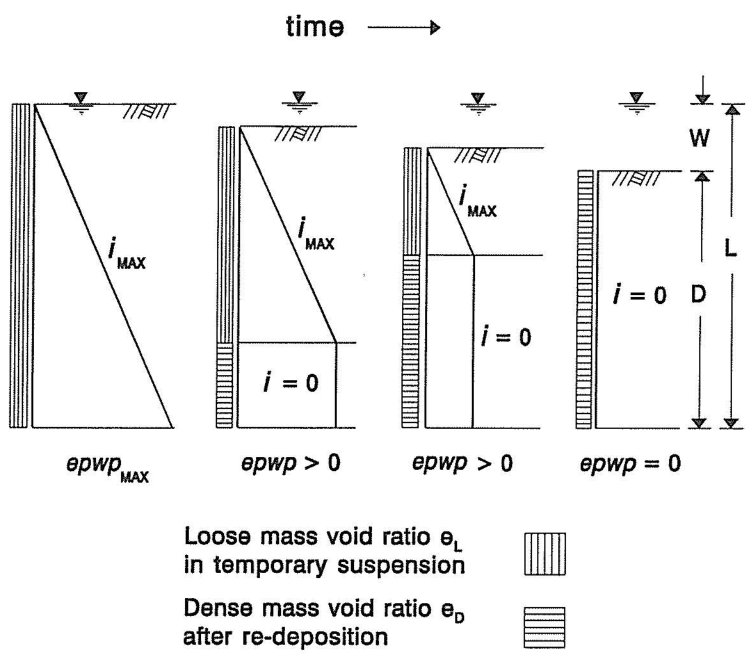


Figure 14. Hydraulic Gradient Demand for Voiding @ V_T

This is the specific particle (sphere) size at which the hydraulic conductivity of the mass is capable of venting water from the voids at a rate which accommodates the intrusion of a particle at a speed of V_T. Essentially, this is a curve of the Hydraulic Gradient ($\boldsymbol{i}=V/\boldsymbol{k}$) which would be necessary to evacuate water from voids for particle encroachment at a rate of V_T. So, when $\boldsymbol{i}=1$ the rate at which water can exhaust voids is equal to the rate at which a particle travelling at V_T would be trying to enter.

Following this line of reasoning, the lower half of the plot, where values of $V_T/\boldsymbol{k}$ are smaller than unity, indicates that as particle size increases beyond the critical/threshold size (D=8 mm), the value of hydraulic gradient required to tolerate intrusion at V_T decreases rapidly, to the point where $\boldsymbol{i}=0.04$ is all that is needed for the coarsest gravels. Since the gradient exists solely for the purpose of making room for the falling particles, it will never be more than necessary to vent the water. Or looked at from a slightly different perspective, the void water is the only source available to supply water through a saturated system of specific conductivity, therefore a gradient cannot be supported beyond that which can convey flow at the rate void volume reduction can produce water. When it is appreciated that V_T is the maximum relative velocity possible in a two-phased system under the influence of gravity it may be seen that Figure 14 represents the worse case scenario. The implication here is that even in the extreme case it is not possible to generate significant ***epwp*** in coarser uniform gravels because of their inherently high hydraulic conductivity.

On the other hand, the upper half of the curve indicates that hydraulic gradients as much as 70 would be necessary in silts and fine sands to permit particle movement at their maximum natural rate of fall. Such gradients are simply not available: The maximum vertical component of internal gradient is $\boldsymbol{i}_{MAX}$ when the two-phased mass is equated to a heavy fluid. For reference, since $\boldsymbol{i}_{MAX}$ depends on void ratio, the values for the loose and the dense packings are indicated on the plot. In this case, since the water is practically incompressible and cannot get out of the way fast enough, it temporarily blocks the progress of the particle. The consequence of this situation is that the solids are kinematically obstructed by the water, and the water must support the full buoyant weight of the solid phase. Therefore, in fine sand for example, where a 10% contraction is enough for V_T to exist,



$$W = L\,\frac{(e_L - e_D)}{(1 + e_L)}$$

Time (t) to zero *epwp* condition

silt or sand	$t = W/k.i$
gravels	$t = W/V_T$

Figure 15. Re-deposition of Collapsed Soil Structure

the low value of ***k*** associated with this size, in combination with pressure gradients restricted to about unity, the system cannot vent interstitial water fast enough, and 100% ***epwp*** will hold the mass in a state of temporary suspension.

Particles in the suspension zone (***k.i***$<V_T$) suffer a complete strength loss, but retain part of their potential energy. Re-deposition of the suspended particles into a viable soil structure, as depicted in Figure 15, does not follow the cohesive consolidation model. After collapse the inadequacy of ***k*** causes a backup of water throughout the full column. The surplus pore water gradually dissipates as the bottom-most layers settle out first, and supernatant water appears above the dropping surface. Once a layer of particles bottoms-out, and its relative motion with the water ceases, it can no longer generate ***epwp***; its effective weight is then fully transferred to inter-granular pressure. Nevertheless, ***epwp*** still exists beneath this level because of the suspended particles higher up the column. Consequently, the re-deposited part of the column does not have a gradient. The rate at which the stable zone builds up is only dependent on the rate water can vent from the suspension zone.

Negative Pore Water Pressure

The position taken here is that negative pore water pressure (***"npwp"***), that is, fluid pressure less than atmospheric pressure, exists in only one of two circumstances:

(a) either because of being in a column supported by surface tension in the capillary zone of a partially saturated mass, or

(b) in response to a tendency towards dilation of the soil structure.

Since this hypothesis is primarily interested in fully saturated masses, and capillarity is dealt with adequately elsewhere, only ***npwp*** associated with deformation of saturated voids will be considered here.

The void water is non-expandable, that is, if we ignore air coming out of solution as pore pressure drops. Consequently, any tendency for the mass volume to increase under deformation will be effected by the void water's capacity to match the rate of volume increase. Dilation takes place where the soil structure is already too densely packed to accommodate any significant particle movements (in response to load changes) without the kinematic need to enlarge the volume of the mass. Under such conditions, it is likely that local cavitation comes about at some critical centre(s) at the instant the dilating force is applied to the mass, with the volume of the affected zone being proportional to the applied force. Pore water pressure at such a location will switch from hydrostatic to the maximum negative value. This mechanism establishes a negative gradient radiating from the dilating centre. The dilating zone is a sink for water which flows under the influence of this gradient, and as water moves in to occupy the vacuum space, the extent of the cavitation, and the ***npwp***, both decrease. ***Npwp*** is thus seen as being tied to the soil structure in a symbiotic relationship (a mutual cause-effect bond): ***npwp*** only exists when the soil structure tries to dilate. It then persists while the inward flow of water, facilitated by the ***npwp*** gradient, accommodates expansion of the structure.

It is important to note the similarities and differences between ***epwp*** and ***npwp*** within a saturated mass, and to acknowledge that ***npwp*** is not a continuous function with ***epwp***.

- Both ***epwp*** and ***npwp*** are a result of structural deformation at a rate too rapid to permit water flow to gain pressure equilibrium through seepage at the prevailing hydraulic gradients.
- ***Epwp*** is generated by particles as they lose potential, whereas ***npwp*** is generated by particles as their potential is being increased.
- ***Npwp*** constrains the particles from moving. ***Epwp*** is a result of particle movement.
- The maximum value ***epwp*** can attain is limited by the amount of overburden above that point, whereas the lower bound value of ***npwp*** is fixed, and is independent of overburden thickness.
- In order for ***epwp*** to create a hydraulic gradient a sink is required to take the surplus water, whereas for ***npwp*** a source is needed to supply additional water to the mass. If these conditions are not met there will be no gradient irrespective of the magnitudes of ***epwp*** or ***npwp***.