# Liquefaction impact revisited

## L'impact de la liquéfaction revisité

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ABSTRACT: Two aspects of liquefaction of carefully prepared partly loosely packed sand are tested: the intensity of a liquefaction trigger and the extent of induced excess pore water pressures when partly liquefaction occurs. The results of several 1D and 3D tests are shown. It appears that hardly any liquefaction happens when the trigger intensity is small. When yet partly liquefaction occurs, significant excess pore pressures arise also in the non-liquefied surroundings. These excess pore pressures slowly diminish during the sedimentation of the liquefied mass. The related densification itself, the porosity decrease, is however so small that the sand remains loose and the likelihood of a new liquefaction to occur due to subsequent new triggers remains. So, if the intensity of a trigger is small and the corresponding liquefied zone is limited, rigorous measures at great expenses are not required to guarantee e.g. stability of buildings and dikes. However, in case a trigger is intense and liquefaction zone is large, its destructive impact can be far reaching particularly due to the related excess pore pressures in a much wider area.

RÉSUMÉ : Deux aspects de la liquéfaction des sables partiellement lâches sont testés: l'intensité du facteur déclenchant d'une liquéfaction et l'étendue des surpressions d'eau induites lorsqu'une liquéfaction partielle se produit. Les résultats de plusieurs essais 1D et 3D sont présentés. Il semble que la liquéfaction est quasi inexistante lorsque l'intensité du facteur déclenchant est faible. Lorsque cependant une liquéfaction partielle se produit, d'importantes surpressions interstitielles apparaissent aussi dans les environs non liquéfiés. Ces excès de surpressions interstitielles diminuent relativement lentement au cours de la sédimentation de la masse liquéfiée. La densification elle-même, et la diminution de la porosité sont cependant si petites que le sable reste lâche et la probabilité d'une nouvelle liquéfaction demeure. Ainsi, si l'intensité du facteur déclenchant est petite et la zone de liquéfaction correspondante est limités, les mesures rigoureuses et coûteuses ne sont pas nécessaires pour garantir par exemple la stabilité des bâtiments et des digues. Cependent, dans le cas où le facteur déclenchant est fort et la zone de liquéfaction est grande, son impact destructeur peut être de grande envergure en particulier en raison des excès de surpressions interstitielles dans une zone bien plus large.

KEYWORDS: sand, mud, density, liquefaction, diffusion, sedimentation, trigger, pore pressure.

## 1 LIQUEFACTION.

Sand deposits in lowlands and delta areas are usually loosely packed. Structures built on top may suffer from weakened support if these sands liquefy. The liquefaction of loosely packed sand is a research topic for many decades and several methods and models are developed. A crucial parameter is the local density (porosity or void ratio). The sensitivity of granular material becoming liquefied is expressed by the so-called liquefaction potential, which can be determined by special laboratory tests on samples from site at various manufactured densities. This counts for dynamic liquefaction (Barends & Ruygrok 1997) and for static liquefaction (Stoutjesdijk, de Groot & Lindenberg 1998). Laboratory results should then be calibrated with the in-situ characteristics to determine the local likelihood of liquefaction. Unfortunately, local characteristics are difficult to measure.

Under a critical loading, e.g. a trigger caused by dynamic shaking (Ishihara 1993) or a static slope slide (Stoutjesdijk e.a. 1998; de Groot e.a. 2006), excess pore pressures will arise and when they reach the actual effective stress level, the granular structure changes into a mud, the state of liquefaction. The liquefied zone depends on the intensity of the trigger. Next, the sand restructures following a sedimentation, characterized by non-linear dispersion and consolidation (Pane & Schiffman 1985). Particularly, fine loose sands are sensitive to this process. When sands are densely packed, negative pore pressures may arise. When the soil liquefies, it behaves like a heavy fluid that induces excess pore pressures into the surrounding soil, which thus may cause shear strength reduction in a much larger area. Some 1D tests and 3D tests have been performed and elaborated to investigate the effect of the intensity of the liquefaction trigger and the extent of induced excess pore pressures in the surroundings.

## 2 EXCESS PORE PRESSURES AT LIQUEFACTION.

### 2.1 *The process and effect of mud sedimentation*

In the laboratory, 1D sedimentation tests have been performed on fine saturated sand with some silt ($d_{10} \sim 60\ \mu$), taken from lake IJssel in the Netherlands. A tube (51 cm high, 8 cm diameter), shown in Figure 1a, is completely filled, covered and rotated 180 degrees, and put at rest in a vertical position while quickly uncovered, in order to simulate dumping this type of sand under water. During the subsequent sedimentation the actual pore water pressure is measured at two positions, at the bottom and half way, by sensors recordings sampled at 200 Hz. As observed, during the sedimentation, segregation of water and fines occurs. In this case, in about 7 minutes a loose sand column of 45 cm high is formed with on top a layer of expelled water (height 3 cm) and a layer of silt (height 2.5 cm).

Figure 1a. The test setup

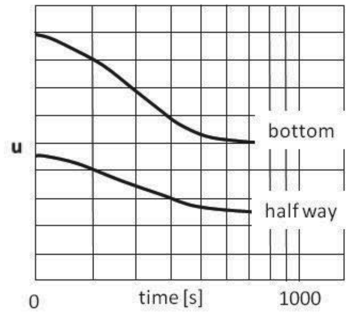



Figure 1b. A typical test result

Remarkably, in the early stage of sedimentation the mud weight causes high excess pore pressures everywhere, nearly two times the hydrostatic pressure, see Figure 1b. A typical test shows a maximum pore pressure gradient of 18.8 kPa/m, at the beginning, representing a mud weight of 18.8 kN/m$^3$. The induced excess pressures dissipate in a way similarly to hindered sedimentation and consolidation, as described by Pane & Shiffman (1985), including Kynch's theory. Although the process locally is highly nonlinear, the period of sedimentation is about proportional to the square of the dissipation path. Therefore, we could define a global sedimentation coefficient, which attains the following value for this material: $s_v = (0.5)^2/7x60 \approx 0.6\ 10^{-3}$ m$^2$/s. In the field the sedimentation time can be roughly obtained with this coefficient for a similar material of thickness $h$ reaching full sedimentation, by using concepts of the consolidation theory, such as $t = 2h^2/s_v$.

## 2.2 *1D liquefaction effect of packing and trigger*

As shown in Section 2.1, during liquefaction large excess pore pressures can exist. It is of interest how these excess pressures proceed in an adjacent densely packed sand formation. In a 1D column test of 100 cm height and 6.5 cm diameter, equipped with six sensors at 12.5 cm sequential distance, recording total pore pressures at a sampling rate of 200 Hz, a two layer sand system was prepared with fully saturated Baskarp B15 sand ($n_{\min} = 0.34$, $n_{\max} = 0.47$, $\gamma_s = 26$ kN/m$^3$). The bottom layer of 42 cm high was placed at a high uniform density at $n \approx 0.34$, and the top layer of 50 cm high was produced at a very low uniform density at $n \approx 0.47$, see Figure 4. The separation between the loose and dense formation was marked by a thin disc of colored sand, see Figure 2. Care was taken to eliminate any air intrusion.

Several test series have been performed. The trigger for liquefying the top layer was produced by rolling a bullet of 0.066 kg over a inclined (20$^o$) gutter impacting the column at about 30 cm height (Figure 2) The intensity of the trigger was changed by the rolling height (from a distance of 5 up to 100 cm over the sloping gutter). After every impact the top level lowering of the loose sand has been measured (Figure 3a). The lower dense sand layer showed practically no densification change, and in the very beginning of every hit some dilatancy (negative excess pore pressures). The intensity of the trigger showed full liquefaction of the loose top layer for a bullet impact after rolling over more than 50 cm over the gutter, for lesser the trigger intensity was too small to invoke complete liquefaction, but excess pore pressures were observed. Next, repeated hits of sufficient intensity showed full liquefaction of the top sand layer each time, followed by sedimentation and consolidation, at a decreasing tendency. The corresponding porosity $n$ and the relative density $I_D$ was determined after each hit (Figure 3b). Many impacts should reach a critical density of $n_{crit} \approx 0.39$ or relative density $I_D \approx 65\%$ (Lindenberg & Koning 1981, Poulos 1971).

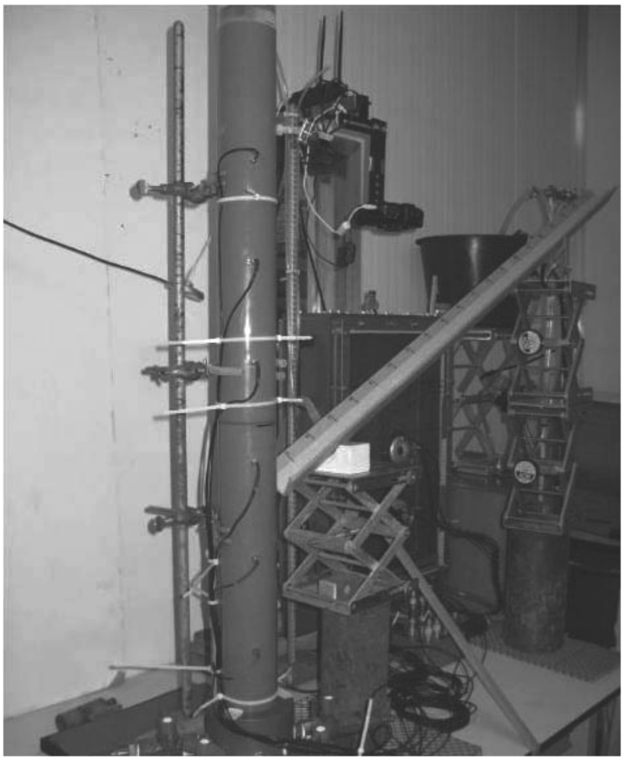
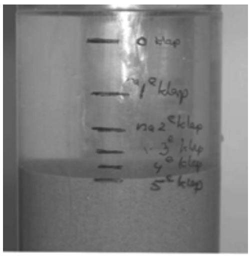


Figure 2. The test setup



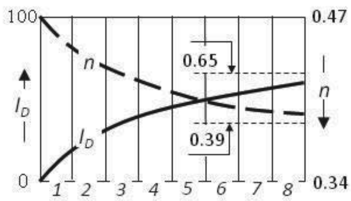



Figure 3a. Top level lowering Figure 3b. Effect at successive hits

The top three sensors (nr 1, 2 and 3), located in the loose sand, showed constant high pore pressure during liquefaction, see Figure 4. The effect of hindered dispersion during sedimentation is noticed by a regular decrease of the pore pressures. Similar related high pore pressures are noticed also in lower sensors, nr 4, 5 and 6, all in the dense sand, also decreasing in accordance with the sedimentation process of the liquefied layer on top. After completion of the sedimentation a hydrostatic situation is restored.

For several hits, sand settlement due to sedimentation is shown in Figure 3a. As it seems, subsequent hits produced a sedimentation period that seems each time about 25% shorter than the previous one. The mud weight was about 18 kN/m$^3$. The sedimentation coefficient (defined in Section 2.1) for the case shown in Figure 4 is: $s_v \approx 1.5\ 10^{-3}$ m$^2$/s. The slight decline of the constant pore pressure during liquefaction phase observed in the top sensors is due to mud passing the sensor during sedimentation. The tests reveal that during partly liquefaction corresponding excess pore pressures extend outside the liquefied zone, and remain high during the sedimentation, In these tests about two minutes. Thicker layers may show significantly longer sedimentation time.

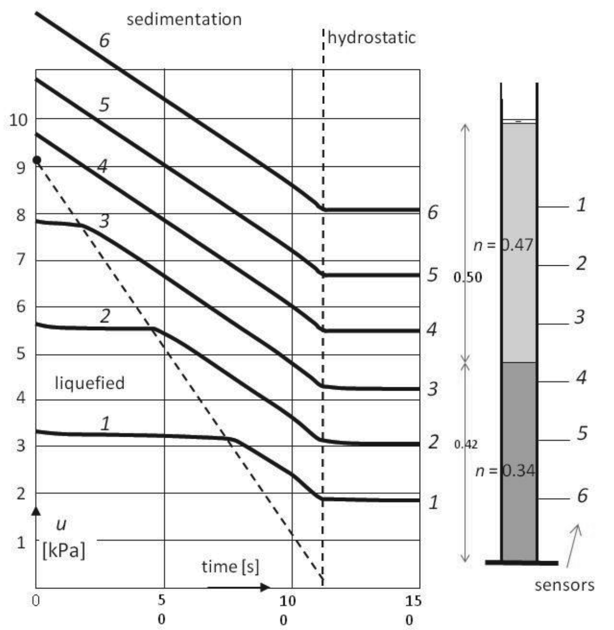



Figure 4. Typical pore pressure recording a full liquefying impact. The inclined dotted line reflects the time of a sensor showing liquefaction; the black spot at the top shows the mud weight: 9.1/0.50 = 18.2 kN/m$^3$.

## 2.3 *3D liquefaction effect of packing and trigger*

### 2.3.1 *Test setup*

In order to understand the three dimensional extent of excess pore pressures induced by partial liquefaction, several 3D tests in a circular tub with a diameter of 58.9 cm and a height of 46.2 cm have been performed. The tub was carefully filled with fully saturated dense sand ($n \approx 0.35$) and in the top centre a small cylinder with a diameter and height of 20 cm was specially prepared with fully saturated loose sand ($n \approx 0.43$), using special equipment and expertise, shown in Figure 5a-c. Baskarp sand B15 ($0.34<n<0.47$, $\gamma_s = 26$ kN/m$^3$) was used.

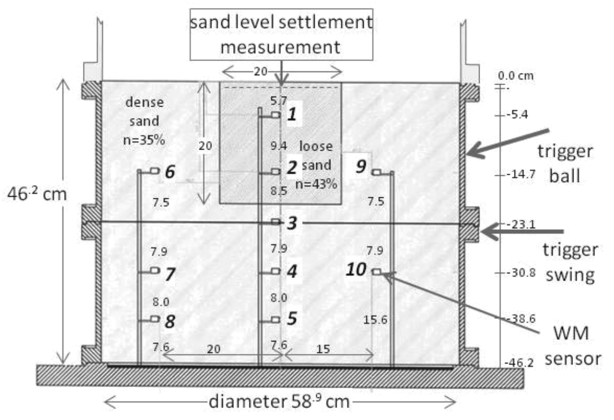
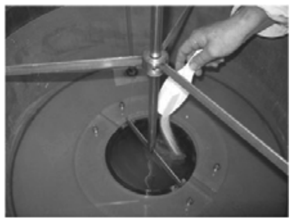



Figure 5a. 3D test setup; WMs are indicated with large italic numbers

Ten micro sensors for measuring pore pressures were placed on a fixed frame, two of which in the centre of the loose sand cylinder (nr 1 and 2) and the others under and aside the loose sand, as shown Figure 5a. From the outside, the tube was subjected to a series of triggers with increasing impact. First five times with a bullet of 0.017 kg and thereafter nine times with a bullet of 0.670 kg, each rolling 100 cm over the gutter at a slope of 20$^o$ (Figure 5d). Next, four impacts by a swing of 5.15 kg from a horizontal distance of 100 cm, subsequently three with a swing weight of 25.6 kg from a horizontal distance of 25, 50 and 75 cm (Figure 5e), and finally the tub was lifted about 10 cm and dropped suddenly, imitating a quake. Thus, in total 21 successive phases were executed. At each impact the sensors recorded the induced excess pore pressures at frequency rate of 200 Hz, and the settlement of the loose sand surface was measured after every phase.



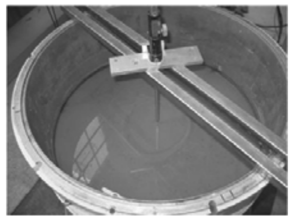
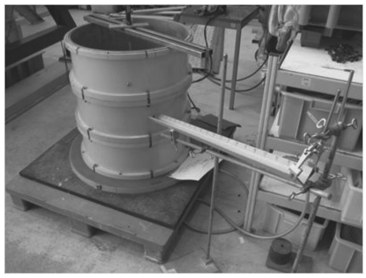


Figure 5b. Preparing loose sand Figure 5c. Ready for testing.



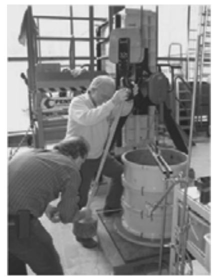


Figure 5d. Rolling trigger bullet system Figure 5e. Trigger swing

### 2.3.2 *Recorded data, excess pore pressures*

Much data was collected and elaborated to illustrate the effect of the trigger intensity and the induced excess pore pressures in the loose sand volume and around in the dense sand. Most relevant data are collected in Table 1.

Table 1. Relevant recorded data during subsequent phases (impacts)

| Phase | Trigger Kg, cm | Liquefaction at WM1 sec | Sedimentation period sec | Settlement cm | WM2$_{max}$ KPa | $n$ % |
|---|---|---|---|---|---|---|
| 1 | | | checking sensors | | | |
| 2 | 0.017 100 | none | 0.8 | 0.04 | 0.412 | 43.0 |
| 3 | 0.017 100 | none | 0.7 | 0.03 | 0.380 | 42.8 |
| 4 | 0.017 100 | none | 0.6 | 0.02 | 0.353 | 42.7 |
| 5 | 0.017 100 | none | 0.6 | 0.01 | 0.335 | 42.7 |
| 6 | 0.67 100 | none | 1.0 | 0.0 | 0.638 | 42.7 |
| 7 | 0.67 100 | not registered, miscommunication ITC and lab | | | | |
| 8 | 0.67 100 | none | 1.0 | 0.0 | 0.600 | 42.7 |
| 9 | 0.67 100 | none | 1.0 | 0.0 | 0.552 | 42.7 |
| 10 | 0.67 100 | none | 1.0 | 0.0 | 0.539 | 42.7 |
| 11 | 0.67 100 | none | 1.0 | 0.04 | 0.542 | 42.6 |
| 12 | 0.67 100 | none | 1.0 | 0.01 | 0.535 | 42.6 |
| 13 | 0.67 100 | none | 1.0 | 0.0 | 0.517 | 42.6 |
| 14 | 0.67 100 | none | 1.0 | 0.0 | *0.500* | 42.6 |
| 15 | 5.14 100 | not registered, miscommunication ITC and lab | | | | |
| 16 | 5.14 100 | 3.0 | 8.0 | 0.25 | 1.43* | 42.2 |
| 17 | 5.14 100 | 2.5 | 6.5 | 0.25 | 1.43* | 41.9 |
| 18 | 25.6 25 | 2.5 | 6.0 | 0.20 | 1.43* | 41.5 |
| 19 | 25.6 50 | 3.3 | 7.0 | 0.20 | 1.43* | 41.2 |
| 20# | 25.6 75 | 3.3 | 7.0 | 0.15 | 1.43* | 41.0 |
| 21 | quake 10 | 3.4 | 7.1 | 0.15 | 1.43* | 40.8 |

* at WM2 the sand was liquefied during about 1 second
[#] Phase 20 taken as reference for determining the porosity

Considering as an indication a sedimentation coefficient $s_v \approx$ 1.5 10$^{-3}$ m$^2$/s similar as in Section 2.2 (same sand), one may conclude that during the Phase 2 with the lightest bullet the liquefied zone reached only the top, less than $h = (s_v t_2)^{0.5} = 3.4$

cm ($t_i$: sedimentation period in Phase $i$). During Phases 2 - 5, the sedimentation factor may have increased to $s_v \approx 2\ 10^{-3}$ m$^2$/s based on a subsequent sedimentation period reduction from 0.8 to 0.6 seconds. For Phase 6, with a heavier bullet, not more than the top $h = (s_v t_8)^{0.5} \approx 4.5$ cm liquefied in the following 9 phases, not reaching position WM1. It should be noted that the sedimentation or self-weight hindered dispersion behaves non-linearly due to the growing inter-particle effect (see e.g. the decreasing trend of recorded excess pore pressures at WM2, during Phases 2 - 5 and Phases 6 - 14, in Table 1). During Phase 15 to 17, with a heavy swing, almost all the loose sand liquefied noticed by periods of constant excess pressures in WM1 (~0.55 kPa) and WM2 (1.43 kPa), shown in Figure 7a.

### 2.3.3 *Phase 20, the 75 cm trigger swing*

Most interesting test is Phase 20. Under the heaviest swing impact, this phase showed full liquefaction of the loose sand volume reaching under WM2, see Figure 7a. The recorded excess pore pressures of WM1 and WM2 during liquefaction reveal a density gradient of (1.430– 0.543)/0.094 = 0.9436. The average mud weight of the liquefied sand is therefore 19.436 kN/m$^3$. Being equal to $(1\text{-}n)\gamma_s + n\gamma_w = 19.436$, it leads to $n_{20} = 0.41$ or a relative density of $I_D = 0.511$. These values have been taken to calibrate the densities of all other tests, as shown in Table 1. The method using the sand surface settlement (Figure 5e) appeared less accurate. The vibrations in the beginning of every record are due to the system frequency, about 25 Hz. They vanish rapidly, within 0.5 seconds. It should be noted that most of the loose sand volume liquefied during Phase 15 to 21, whereas lighter triggers used beforehand during Phase 1 to 14 did only liquefy just the top part above WM1.

In the very early stage (during each Phase), dilatancy caused negative pore pressure almost everywhere in densely packed sand during a rather short period (less than 0.02 seconds). In Phase 20, the sedimentation period after liquefaction took about 7 seconds, and everywhere, both in the loose and in the dense sand significant excess pore pressures were observed during this sedimentation period. Phase 21, which revealed similar effects as Phase 20, can be viewed as an act of a quake, a 10 cm sudden drop of the entire tub. This implies that quite some energy is required to really liquefy loose sand deposits. However, if liquefaction occurs the sedimentation process of the liquefied mud induces significant excess pore pressures reaching far aside and underneath the liquefied zone for as long as the sedimentation process takes.

## 3 CONCLUSIONS

The intensity of a liquefaction trigger and the extent of induced excess pore water pressures when partly liquefaction occurs are investigated by 1D and 3D tests. Hardly any liquefaction happens when the trigger intensity is small. However, if liquefaction occurs, significant excess pore pressures will arise also in the non-liquefied surroundings and they diminish slowly during the sedimentation period, affecting metastability regions (Stoutjesdijk e.a. 1998). The related densification itself, the porosity decrease, is yet quite small, so that the probability of a new liquefaction remains. In conclusion, if the likelihood of an intensive trigger is small and liquefied zone limited, rigorous measures at great expenses are not required to guarantee e.g. stability of buildings and dikes. However, in case a trigger may be intense and liquefaction zone is not small, its destructive impact can be far reaching particularly due to the related excess pore pressures in a much wider area. It is suggested to translate these findings to site situations and formulate proper guide lines.

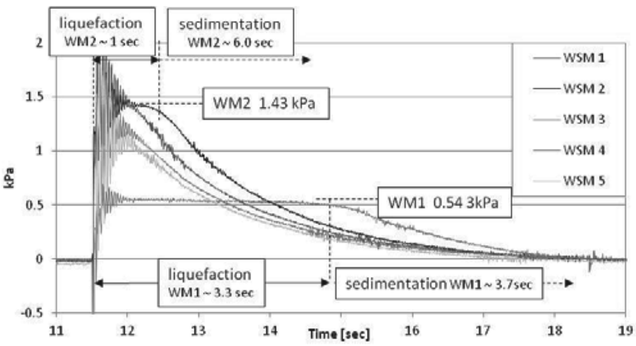



Figure 7a. Excess pore pressures WM1 to WM5 during Phase 20

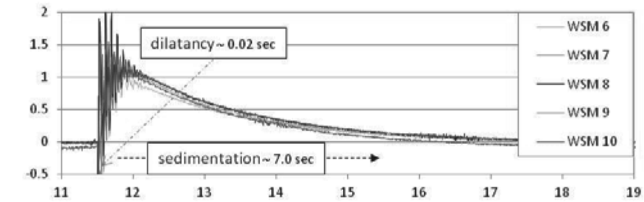



Figure 7b. Excess pore pressures WM6 to WM10 during Phase 20

## 4 ACKNOWLEDGEMENT

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## 5 REFERENCES

Barends, F.B.J. & Ruygrok, P. 1997. The cyclic liquefaction potential of a submerged cohesionless sand bed: a practical method. *Proc BOSS'97, Elsevier Science Ltd* (1),71-84.

de Groot, M.B., Bolton, M.D., Foray, P., Meijers, P., Palmer, A.C., Sandven, R., Sawicki, A. & Teh, T.C. 2006. Physics of liquefaction phenomena around marine structures. *ASCE Journal of Waterway, Port, Coastal and Ocean Engineering*, 132: 227-243.

Lindenberg, J. & Koning, H.L. 1981. Critical density of sand. *Géotechnique* 31 (2) 231-245.

Ishihara, K. 1993. Liquefaction and flow failure during earthquakes. *Géotechnique* 43 (3) 351 –451

Pane, V. & Schiffman, R.L. 1985. A note on sedimentation and consolidation. *Géotechnique* 35 (1) 69-72.

Poulos, S.J. 1971. The steady state of deformation. *Geot Eng. Div. IASCE* 107 (GT5) 553-562.

Stoutjesdijk, T.P., de Groot, M.B. & Lindenberg, J. 1998. Flow slide prediction method: influence on slope geometry. *Can. Geotechn. Jl.* 35 (1) 43-54