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A review of permeability in liquefied sands

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ABSTRACT: Loose saturated sands often experience a significant reduction in effective stress under dynamic loading, leading to reduced shear strength. The soil permeability in the liquefied state is one of the major factors governing the duration and magnitude of this strength loss. Results from both 1g shake table tests and centrifuge experiments have demonstrated that permeability during liquefaction can increase dramatically and may later decrease to slightly below original values after excess pore pressures have dissipated. This paper presents a review where results from multiple dynamic studies on saturated sands, both at 1g and centrifuge conditions are discussed. Accurately characterizing permeability in the liquefied state is vital in understanding the behaviour of saturated sands under dynamic conditions, including pore pressure dissipation patterns, shear strength recovery, and post-liquefaction reconsolidation. The outcome would be a better understanding of these processes to determine soil behaviour under seismic and dynamic loads.

1 INTRODUCTION

1.1 Background

Soil liquefaction and its associated effects have emerged to be of key interest to the geotechnical engineering community following the 1964 Niigata Earthquake in Japan. The phenomenon can be explained as the loss of soil's shear strength in saturated sands due to rise in excess pore water pressure caused by rapid ground motions. The study of earthquake induced soil liquefaction has classically been taken as undrained due to its instantaneous nature, where no volume change or settlement is expected to occur. Contrary to the above, results from dynamic centrifuge tests and field observations show significant amount of ground settlements both during and after the ground motions.

The fact that soil liquefaction is not a perfectly undrained phenomenon has been pointed out in several studies (Madabhushi and Haigh, 2012; Adamidis and Madabhushi, 2018; Du, 2018). The expulsion of pore water occurs in response to the elevated pore water pressures. Hence, the excess pore pressures are dissipated through a vertically upward seepage flow. Soil permeability is a vital parameter concerning such seepage in soils and consequently affecting the settlement response of saturated sands.

1.2 Literature Review

Researchers have made several attempts to track the variation in permeability of liquefied sands through 1g tests (Ha et al., 2003; Haigh et al., 2012; Wang et al., 2013; Ueng et al., 2017; Du, 2018) as well as dynamic centrifuge tests (Hushmand et al., 1987; Arulanandan and Sybico, 1992; Su et al., 2009). The permeability during the dynamic shaking has been found to increases above the static permeability value. Various numerical studies used along with results from centrifuge tests have also indicated about the rise in permeability during soil liquefaction (Taiebat et al., 2007; Shahir et al., 2012; Ma et al., 2025). Permeability is a critical parameter in numerical models that influences the buildup of excess pore pressures and liquefaction induced settlements. Arulanandan and Sybico (1992) have attributed the increased permeability in the liquefied state to the dynamic shaking which is referred to as the 'agitation effect'.

The studies involving 1g element tests have tried to measure the permeability. Haigh et al. (2012) and Ueng et al. (2017) utilised the constant flow permeability tests with upward seepage in 1g sand columns for their study. Du (2018) determined the permeability after full liquefaction through cyclic triaxial apparatus. Ha et al. (2003) and Wang et al. (2013) resorted to 1g shake table tests to study the dissipation of excess pore pressures during liquefaction. The settlement characteristics were processed to estimate the permeability in liquefied state.

Dynamic centrifuge studies have also been largely employed to study liquefied sands. Arulanandan and Sybico (1992) used data from electrical resistivity probe installed in centrifuge to study the changes in pore structure and its effect on permeability. Many researchers have relied on numerical techniques to analyse the settlement data and reconsolidation characteristics from dynamic centrifuge tests. Su et

Table 1. Summary of 1g tests with soil characterisation and testing conditions.

Reference	Test Type	Peak Acceleration (m/s^2)	Duration of shaking (s)	Prototype Height (m)	Sand Type	Pore Fluid	D_{50} (mm)	Relative Density (%)	k_r
Ha et al. (2003)	Shake table	1.47	~5	0.4	Jumunjin	Water	0.57	30 & 50	~5.0
					Youngjong		0.16	20 & 40	~1.4
					Incheon1		0.34	21 & 43	~2.8
					Incheon2		0.5	23 & 45	~2.0
					Han river		0.5	20 & 41	~1.8
Haigh et al. (2012)	Sand column (seepage, no vibration)	-	-	0.24	Fraction E	Water	0.12	46	~5.0
					Fraction D		0.3	54	~2.0
					Hostun		0.47	44	~1.1
Wang et al. (2013)	Shake table	3	~13	0.6	Toyoura	Water & Polymer fluid	NA	35 - 45	1.2-4.0
Ueng et al. (2017)	Sand column (seepage and vibration)	588.6	~6	0.5	Vietnam Silica	Water	0.32	40.7 & 51.6	4.0-5.0
Du (2018)	Triaxial permeability after cyclic shearing	-	-	0.076	W9 Silica	Water	0.31	35 - 45	~2.0

Table 2. Summary of dynamic centrifuge tests on fine uniformly graded Nevada sands with water as pore fluid.

Reference	g-level	Peak Acceleration (m/s^2)	Duration of shaking (s)	Prototype Height (m)	Depth of Liquefaction (m)	*k_static* ($\times 10^{-5}$ m/s)	D_{10} (mm)	Relative Density (%)	k_r
HMD-1987[a]	50	5	~18	11.29	11	1.000×50.0	0.10	44	~2.0-5.5
A&S-1992[b]	50	3.5	~20	9.52	7.14	6.560×50.0	NA	NA	~6.0-7.0
VELACS[c]	50	2.2	~13	10	5.62	6.583×50.0	0.09	40	~4.0-6.5[e]
Kramer 1[d]	22.5	1.4	~6	6	1.52	6.112×22.5	0.12	40	~4.5-5.0[e]
Kramer 2[d]	22.5	1.4	~15	6	1.55	6.112×22.5	0.12	40	~3.0-8.0[e]
Kramer 3[d]	22.5	2.2	~50	6	2.42	5.656×22.5	0.12	50	~7.5-9.5[e]
Kramer 4[d]	22.5	4	~30	6	2.52	5.656×22.5	0.12	50	~1.7-5.0[e]

[a] after Hushmand et al. (1987), [b] after Arulanandan and Sybico (1992), [c] after Arulanandan and Scott (1993), [d] after Kramer (2009), [e] after Ma et al. (2025).

al. (2009) applied physical law of conservation to numerically analyse the settlement data to obtain the permeability. Ma et al. (2025) applied a fully coupled solid-fluid formulation on results from a few previous centrifuge studies to back-analyse the permeability. The outcomes of these studies and their limitations will be discussed in later sections.

2 DISCUSSION

The permeability ratio, k_r is defined as the ratio of permeability in liquefied state during dynamic shaking to the permeability in static conditions. Though the increase in permeability during liquefaction has been well understood, there is little clarity on the typical range of the permeability ratio. Significant variation can be observed in the range of permeability ratio obtained in the different studies.

Haigh et al. (2012) studied the permeability for three different sands at low effective stresses in sand column without applying any vibration. Whereas Ueng et al. (2017) used fine Vietnam silica sand in their 1g sand column tests along with external vibration. Both the above studies have found the liquefied permeability to increase up to 5 times the static value. Du (2018) in their cyclic triaxial study found the permeability immediately after liquefaction to rise around 2 times of the original.

In the 1g shake table study by Ha et al. (2003) where five different sands were investigated, the permeability ratio was observed to be in range of 1.4 – 5.0. Wang et al. (2013) through their shake table tests on Toyoura sand found the permeability ratio to lie in the range of 1.2 – 4.0. Table 1 presents a detailed summary of these 1g studies including the soil characterisation and the testing conditions.

A set of dynamic centrifuge studies conducted with uniformly graded fine Nevada sands with water as the pore fluid are summarised in Table 2. The scaled permeability for high gravity static conditions is defined as *k_static* in Table 2. Su et al. (2009) in their study on Toyoura sands also found the increase in permeability of up to 6 times the static value. The centrifuge studies with similar soil and testing conditions summarised above are so chosen to create a common ground for comparison of test results and avoid any non-uniformities in scaling. It can be assumed that the effect of pore fluid does not affect the computation of k_r as both the static and the liquefied permeability values are considered at Ng condition, therefore no scaling is required.

The variations in the permeability ratio as obtained in the above-mentioned studies can be attributed to several factors. It needs to be pointed out that the depth of liquefaction and model varies in each case. It should also be noted that value of permeability obtained in the above cases is usually a spatial average over the depth of the liquefaction. This may vary with the intensity of the applied dynamic shaking. Hence, the result obtained can vary even for the same sand compacted to the same relative density. Results from Du (2018) show that although the permeability decrease with depth, the permeability ratio after liquefaction is apparently independent of depth. However, further investigations need to be carried out to ascertain the effect of depth on the permeability ratio.

3 CONCLUSION

Soil permeability is a key parameter affecting the pore pressure dissipation and settlement characteristics in liquefied sand deposits. Hence, accurate measurement of permeability is vital to get a better understanding of liquefied sand behaviour. The effect of depth on the permeability ratio, k_r needs to be further investigated to understand the trend of the spatial average. Triaxial permeability test needs to be evaluated to obtain the representative dynamic permeability as triaxial test setup is suitable for assessing different depths of overburden. Appropriate validations need to be carried out with the aid of dynamic centrifuge tests to ascertain the corroboration of both approaches. The outcomes would help guide better modelling of soil liquefaction.

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