Recent Advances in Liquefaction of Soils

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Abstract. The huge damage has been observed in recent past earthquakes due to liquefaction or related phenomena. This is despite the fact the liquefaction is widely studied worldwide. This is perhaps because many of the issues related to liquefaction resistance of soils are still unresolved. The paper reviews state of the art for liquefaction of soils. It also elaborates some of the recent advances in this area. Some of the work done by author and his research group has been presented. These advances are related to the effect of fines, effect of reinforcement on the liquefaction resistance of soils. Further, assessment of liquefaction resistance (and potential) under cyclic loading using laboratory tests and in-situ tests has been discussed. Advanced ongoing research for numerical modeling and for mitigation of liquefaction have also been discussed. The results presented here are those which are already published by author and his research group.

Keywords: Liquefaction, Fine Contents, Reinforcement, Numerical Modelling Mitigation.

1 Introduction

One of the major causes of destruction during an earthquake is the failure of the ground structure. The ground may fail due to fissures, abnormal or unequal movements, or loss of strength. The loss of strength may take place in sandy soils due to an increase in pore pressure. This phenomenon, termed *liquefaction*, can occur in loose and saturated sands. The increase in pore pressure causes a reduction in the shear strength, which may even be lost completely. Soil that has lost all shear strength behaves like a viscous fluid. When soil fails in this manner, a structure resting on it simply sinks into it.

It was observed often during past earthquakes that the liquefaction of saturated loose sands has been the cause of severe damage to various buildings and other structures. The catastrophic nature of this type of failure attracted the attention of researchers in this area and some work has been reported to evaluate liquefaction susceptibility e.g. Seed and Lee (1966), Seed and Idriss (1971), Seed et al. (1976), Prakash (1981), Seed et al. (1985), Kramer (1996), Youd et al. (2001), Idriss and Boulanger (2006).

Extensive work has been carried out by author and his students for liquefaction studies. Singh (2009) examined the effect of reinforcement on liquefaction resistance of

Solani sand (Maheshwari et al., 2012, 2013, Saran et al., 2010) and effect of stone columns on liquefaction resistance of pond ash (Singh et al., 2010). Senapati (2012) investigated the liquefaction resistance of geogrid reinforced soil using shake table (Senapati and Maheshwari, 2012). Patel (2006) examined the effect of fines on liquefaction potential (Maheshwari and Patel, 2010). The liquefaction resistance has been also studied in the laboratory using cyclic triaxial system by Choudhary (2010) and Verma (2016). Muley (2016) accessed the liquefaction potential of Roorkee region using field and laboratory approach (Muley et al., 2015). Muley et al. (2012) examined the effects of fines on liquefaction resistance of Solani sand. Kumawat (2014) and Singh (2015) examined the liquefaction potential using cone penetration tests (Kumawat and Maheshwari 2010). Maheshwari et al. (2008) evaluated the liquefaction susceptibility of soils in the Himalayan region.

Kanth (2016) is carrying out the numerical modeling of liquefaction resistance simulating with laboratory test results (Kanth and Maheshwari, 2018, 2019). Gowtham (2019) has initiated research work to mitigate the liquefaction using pre-fabricated vertical drains (Gowtham and Maheshwari, 2020). In the current manuscript some of the results drawn by author and his research group and already published are summarized. Particular emphasis is given on the effect of reinforcement and effect of fines on liquefaction resistance.

2 Effect of Reinforcement

Background: A number of studies have been conducted relating to the behaviour of soil reinforced with randomly distributed fibers and mesh elements under static conditions. Various types of randomly distributed elements such as polymeric mesh elements (Andrews et al. 1986), synthetic fibers (Gray and Ohashi 1983; Maher and Gray 1990; and Ranjan et al. 1994) and Coir fibers (Banerjee et al. 2002, Sivakumar Babu and Vasudevan 2008) had been used to reinforce soils. It was shown that the addition of randomly distributed elements to soils contribute to increase in strength and stiffness.

However, the studies on behaviour of soils reinforced with randomly distributed elements under cyclic loading are very limited in the literature. Krishnaswami and Isaac (1995) explored the feasibility of the reinforced earth technique as a counter measure to liquefaction. Boominathan and Hari (2002) also conducted the similar studies with fly ash reinforced with geosynthetic fibers and mesh elements and found that the liquefaction resistance of fly ash significantly increased. However, all these studies were on small size (diameter 38 mm or 50 mm) samples using the cyclic triaxial apparatus and no study has been reported with large size sample test on the assessment of liquefaction using the shake table (vibration table) apparatus. Also in none of the above studies, the use of geogrid sheets and synthetic fiber for improving the liquefaction resistance of granular material has been demonstrated. Shake tables are capable of reproducing the motion of the ground during an earthquake allowing for controlled testing of structures subjected to earthquakes (Finn, 1972, DeAlba et al., 1976).

Summary: Maheshwari et al. (2012) reported liquefaction resistance of Solani sand reinforced with Geogrid Sheet, Geosynthetic Fiber and Natural Coir Fiber. Tests were carried out on shake table with sand samples prepared at relative density of 25% without and with reinforcements. Fig. 1 shows the shake table used to conduct the experiments for liquefaction studies (Gupta, 1977). In this table, the frequency and amplitude of excitation can be controlled. Synthetic geogrid sheets were used in three different combinations of 3 layers, 4 layers and 5 layers. In case of fibers, the percentage of fibers by weight of dry sand were taken as 0.25 %, 0.50 % and 0.75 % and mixed randomly with the sand sample.

Fig. 1. Liquefaction Table used in the Experiments at IIT Roorkee

The maximum pore water pressure (U_{max}) was measured corresponding to various levels of accelerations varying from 0.1g to 0.4g. The frequency of dynamic load was kept constant at 5Hz. The liquefaction resistance of sand was evaluated in-terms of maximum pore water pressure ratio (r_{umax}). The pore water pressure ratio (r_u) is defined as:

$$r_u = \frac{U}{\sigma'_{vo}} \tag{1}$$

Where U is excess pore water pressure and σ_{vo}' is the effective overburden pressure.

Test results indicated that on inclusion of fibers and geogrid sheets into the sand samples, the r_{umax} decreased. It was also observed that on increasing the fiber content and number of geogrid sheets, r_{umax} decreased further and this decrease is significant at small amplitude of excitation. The average increase in liquefaction resistance of sand reinforced with synthetic and coir fibers was found to be 88 % and 91 % respectively for 0.75 % fiber content, whereas for 5 layers of geogrid sheets, this increase was about 31% at 0.1g acceleration. Some of the results are presented here.

2.1 Effect of Geogrids

Fig. 2 shows the variation in excess pore water pressure with time for sand reinforced with 3 layers at an acceleration of 0.1 g. It was observed that the trends of rise of pore water pressures for all the points were similar to those observed without geogrid. However, the magnitude of pore water pressures developed at all the three points i. e. top, middle and bottom are less than that of plain sand and this resulted into decrease in the value of maximum pore water pressure ratio r_{umax}, marked on each curve.

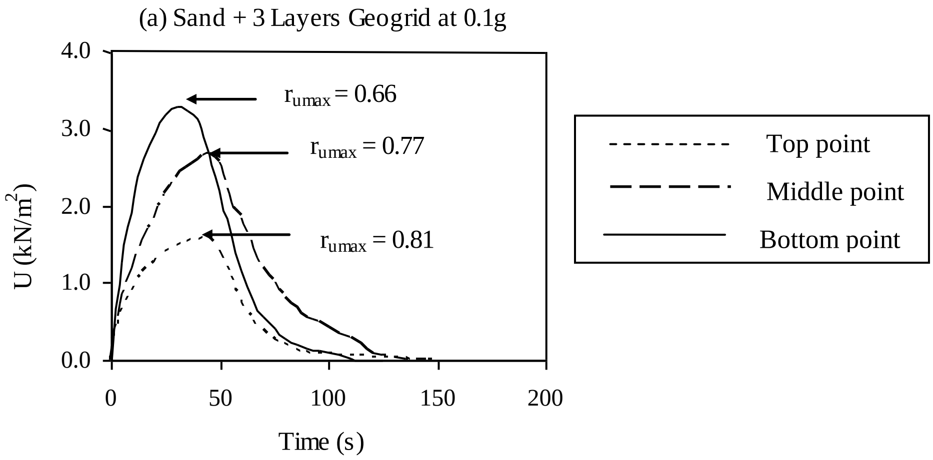

Fig. 2. Excess Pore Water Pressure with Time for Sand with 3 layers of Geogrid Sheet at an acceleration of 0.1 g (after Maheshwari et al., 2012)

Due to geogrid, the value of r_{umax} decreased significantly, this indicated that liquefaction resistance of sand was increased. It was also observed that the liquefaction resistance of sand is further improved with increasing number of geogrid sheets and the amount of settlement decreases significantly due to reinforcement and this decrease is higher for higher number of geogrid sheets. Thus it can be inferred that the liquefaction resistance of Solani sand increases, if it is reinforced with geogrid sheets.

2.2 Effect of Coir Fibers

Fig. 3 shows the variation in excess pore water pressure with time for sand reinforced with 0.25% of coir fiber at an acceleration of 0.1 g. It can be observed that the trends of rise of pore water pressures for all the points were similar to those observed for sand with geogrid. The magnitude of pore water pressures were significantly less than that of plain sand and this resulted into decrease in the value of maximum pore water pressure ratio r_{umax}, marked on each curve. The effect of coir fiber was very significant. For 0.25%, 0.5% and 0.75% of coir fiber, the average value of r_{umax} decreased from unity to about 0.3, 0.22 and 0.09, respectively. Thus, liquefaction resistance of sand was increased by a margin of 70%, 78% and 91%, respectively due to coir fiber.

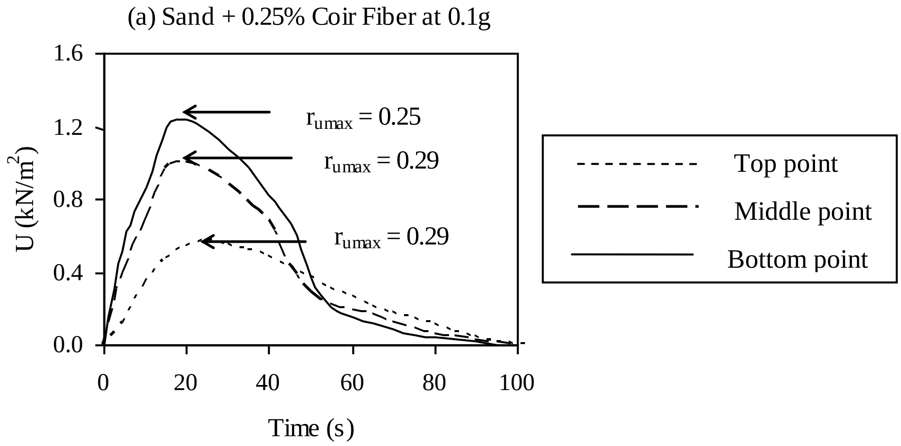

Fig. 3. Excess Pore Water Pressure with Time for Sand with 0.25% Coir Fiber at an acceleration of 0.1 g (after Maheshwari et al., 2012)

It was observed that inclusions of coir fiber into sand reduced the amount of settlement significantly. This is attributed to the fact that coir fiber makes Solani sand a composite material whose strength and stiffness is higher than that of sand alone. The coir fiber was very much effective in increasing the liquefaction resistance of sand. The Solani sand which is prone to liquefaction at 25 % relative density will not liquefy and will remain intact during earthquakes, if it is reinforced with coir fiber.

2.3 Effect of Synthetic Fibers

Fig. 4 shows the variations in excess pore water pressure with time for sand reinforced with 0.25% of synthetic fiber at an acceleration of 0.1 g. It can be observed that the trends of rise of pore water pressures for all the points were similar to those observed with sand reinforced with coir fiber. The magnitude of pore water pressures developed were less than that of plain sand and this resulted into decrease in the value of maximum pore water pressure ratio r_{umax} marked on each curve. The effect of synthetic fiber is tremendous as it decreases the values of r_{umax} significantly from unity. It was also observed that the inclusion of fiber into the sand reduces the amount of settlement significantly. Therefore, the use of synthetic fiber is very much effective for increasing the liquefaction resistance of Solani sand.

It was inferred that the use of synthetic and coir fiber is the better choice than the geogrid sheet for the substantial increase in liquefaction resistance of sand. It was also observed that the coir fibers give higher liquefaction resistance value than that indicated by synthetic fibers for all levels of accelerations and fiber contents.

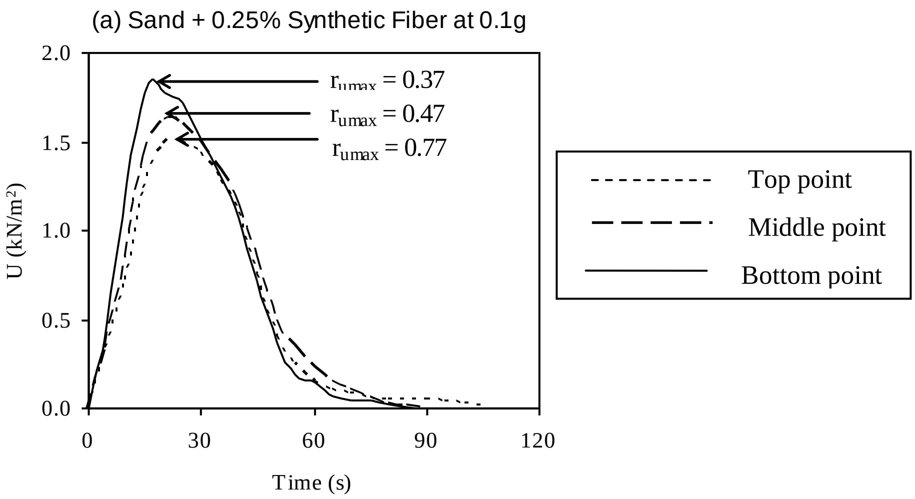

Fig. 4. Excess Pore Water Pressure with Time for Sand with 0.25% Synthetic Fiber at an acceleration of 0.1 g (after Maheshwari et al., 2012)

3 Effect of Fines

Background: It has been understood that the presence of silt and clay particles will in some manner affect the resistance of sand to liquefaction. However, a review of studies published in the literature indicates that no clear conclusions can be drawn as to in what manner altering the fines content affects the liquefaction resistance of a sand under cyclic loading. This is particularly true for soils containing non-plastic fines. Studies have reported that increasing the silt content in sand may increase or decrease the liquefaction resistance of the sand, or increase the liquefaction resistance until some critical silt content is reached. Both clean sands and sands containing fines have been shown to liquefy in the field (Prakash 1981, Kramer 1996).

Based upon case histories of actual soil behavior during earthquakes, there is evidence that soil with greater fines contents are less likely to liquefy in a seismic event. While some research reports have shown that an increase in fines content results in an increase in liquefaction resistance, other has shown the opposite effect. Chang et al. (1982) noted that case studies reveal that most liquefaction resulting from earthquakes has occurred in silty sands and sandy silts.

Seed et al. (1985) modified the cyclic resistance ratio (CRR) versus normalized SPT blow count curves originally proposed by Seed and Idriss (1971) to account for the increase in liquefaction resistance provided by increased fines content. The revised chart provides a series of curves for 5 percent, 15 percent, and 35 percent fines. These curves indicate that a larger CRR is required to liquefy a soil with higher fines content for a given blow count. Several investigators have found that the cyclic resistance of a sandy soil increases with increasing silt contents. Koester (1994) found that for specimens prepared to a constant gross void ratio, as silt content increased the cyclic resistance of the soil decreased until some limiting silt content was reached at which point the cyclic resistance began increasing.

Summary: Maheshwari and Patel (2010) presented the effects of non-plastic silts on liquefaction potential of Solani sand. Tests have been conducted on the vibration table at different accelerations and pore water pressure is measured. During the lab investigation, locally available Solani Sand and Dhanauri Silt have been used. The soil samples have been prepared by varying silt content and the initial relative density. The results of the study performed are used to clarify the effects of non-plastic fines content on the Solani sand. As the silt content increases, the number of cycles required to produce maximum pore water pressure increases. For a particular level of excitation, rate of pore water pressure generation is maximum at critical silt content. It is observed that critical silt content to generate maximum pore water pressure is different for different accelerations. Further, effect of silt content is very much dependent on relative density.

3.1 Effect of Silt Content

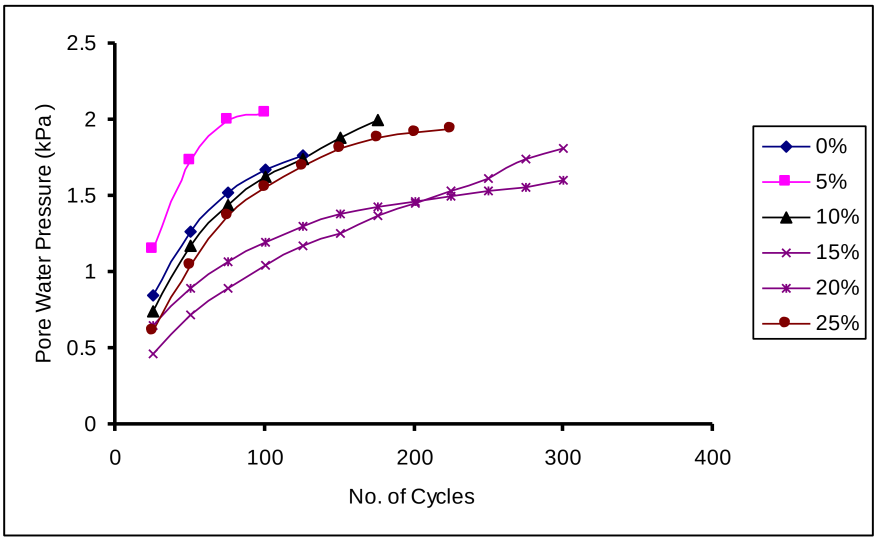

Fig. 5. Variation in Pore Pressure with Number of Cycles for Different Silt Contents at 0.3g acceleration (after Maheshwari & Patel, 2010)

Fig. 5 represents the pore water pressure generation with number of cycles for different silt contents for 0.3g acceleration. As the number of cycles increases, the pore water pressure increases for all the silt contents, which is as expected.

Also, it has been observed that the generation of pore water pressure is minimum for 5% silt content as compared to the soil sample without silt. Further it can be observed that the pore water pressure generation, decreases as silt content increases beyond 5%. Thus for 0.3g acceleration, critical silt content is 5%. The trend of these results was similar to that presented by Prakash and Sandoval (1992).

From the tests conducted at 0.4g acceleration and 0.6g acceleration, it was observed that the critical silt content (for which maximum pore water pressure is observed) is not unique and very much dependent on the level of excitation.

4 Assessment of Liquefaction Potential using Field and Laboratory Approach

Background:

Many researchers reported evaluation of liquefaction potential using field and laboratory tests. Based on grain size, Seed and Idriss (1971) proposed the method to determine equivalent uniform average shear stress due to an earthquake. Seed (1979) developed a method to estimate liquefaction potential for sand under level ground conditions using Standard Penetration Test (SPT) data. This method was based on field data for the sites, which either had or not experienced liquefaction due to earthquake loading. Seed *et al.* (1983) presented empirical methods for evaluating liquefaction of sands and silty sands by SPT-N value.

Seed *et al.* (1985) developed SPT based method to estimate the liquefaction potential for sands. The field data were reinterpreted and plotted in terms of $(N_1)_{60}$. i.e. the N value determined by SPT tests in which the driving energy in drill rod is 60% of the theoretical free fall energy and normalized overburden pressure of 1 ton/ft^2 (100 kPa). Liquefaction curves for sands with different $(N_1)_{60}$ value and different fine contents were proposed (Seed *et al.*1985). Youd and Idriss (1997), Youd *et al.* (2001), Cetin et al. (2004), Idriss and Boulanger (2006) and Boulanger et al. (2012) extended previous studies on the use of SPT data for evaluation of liquefaction resistance.

Summary:

Few studies for liquefaction susceptibility were conducted using the Solani sand e.g. Choudhary *et al.* (2010). Muley et al. (2015) evaluated the liquefaction potential of soil in Roorkee region. For this purpose, soil samples from different places in Roorkee region are collected. Field data from 5 representative boreholes were collected using SPT to know the N values and soil profile for geotechnical investigation. The factor of safety against liquefaction was evaluated at different depths for all the sites using both field and laboratory data. It was found that the factor of safety against the liquefaction using field approach is marginally greater than that using the laboratory approach for all the sites. Also the factor of safety using ground response analysis is significantly smaller than that using simplified method. Thus it was concluded that use of simplified method may not be adequate. For example, typical result of a site in Haridwar is presented in Fig. 6.

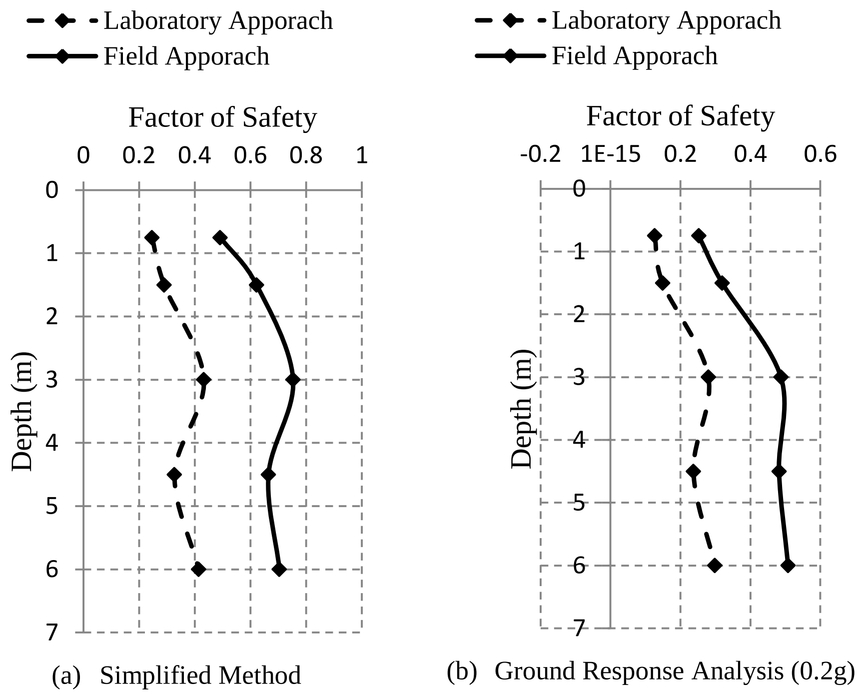

Fig. 6 Factor of Safety against Liquefaction by Field and Lab Tests for Haridwar City Site (after Muley et al., 2015)

5 Numerical Modeling of Liquefaction Resistance

Numerical modeling for liquefaction is rarely reported. Modeling liquefaction of soil numerically is a complicated task, as it involves generation of pore water pressure. Thus, evaluation of pore water pressure with accuracy is important. PLAXIS has implemented UBC3D-PLM as a user defined material soil model, which is formulated specifically for liquefaction analysis and is efficient enough to model the onset of liquefaction and post liquefaction behavior as well. Kanth and Maheshwari (2019) presented the key features of UBC3D-PLM and parameters governing them. The highlighted key features are namely, plastic potential function, soil densification rule, secondary yield surface, and post-liquefaction factor. The work illustrated is divided in three parts. Firstly, evaluation of material model parameters using empirical relations, this evaluation is done for Solani sand. Secondly, evaluated parameters are validated in PLAXIS carrying out available test simulations. Lastly, the results obtained from numerical simulations using UBC3D-PLM are compared with those obtained on cyclic triaxial by conducting undrained triaxial compression and undrained cyclic triaxial tests, which covers both static and dynamic loading conditions, respectively.

6 Mitigation of Liquefaction using PVDs

Author and his research group are also working in the area of mitigation of liquefaction. Recent work is using pre-fabricated vertical drains (PVDs) where the effect of these measures on liquefaction is being investigated by conducting the experiments on liquefaction table. Also other mitigation measures such as sand compaction piles (Gowtham and Maheshwari 2020) are being examined.

7 Summary and Conclusions

Liquefaction is a complex issue and studied widely by many researchers, however, many of the issues are still unresolved. The author and his research group at IIT Roorkee attempted to resolve some of the issues and key findings are already published. The manuscript presents some of the key results related to the effect of reinforcement and effect of fines on liquefaction resistance. Further, assessment of liquefaction potential using field and laboratory approaches are discussed. The author and his team are currently working for numerical modeling for liquefaction resistance and mitigation measures for liquefaction.

8 Acknowledgement

The results presented in the manuscript are those already published by author and his research group as cited in the manuscript. Therefore it is acknowledged that this is not an original manuscript rather summarizes works done by author and his students over the years for liquefaction studies.

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