The apparent viscosity to model the behaviour of liquefied sands

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ABSTRACT

The liquefaction induced loss of soil strength and stiffness marks a change of soil state, that switches from solid to liquid. Recently, the research has revealed that when liquefaction is attained, the soil behaves as a non-Newtonian fluid. Therefore, the framework of soil mechanics cannot be adopted and then the soil behaviour should be studied using a fluid mechanic approach. Several research works highlighted the large potentiality of the apparent viscosity (η) as the parameter ruling both the liquefaction triggering and the behaviour of liquefied sands. Mele (2022) showed that liquefied sands exhibit a shear-thinning behavior (i.e. decreasing viscosity with increasing shear strain rate), highlighting the direct link between k and n (parameters of shear-thinning model) to the soil demand (CSR). This paper aims to confirm the proposed correlations of Mele (2022) passing from small to full scale. To do that, the results of 1D non-linear site response analysis of the well-known case study of Treasure Island (California), affected by extensive liquefaction phenomena during the 1989, have been studied and interpreted with a “viscous perspective”. The good agreement of the calibrated pseudo-plastic law with the results of the dynamic analysis confirms, the relevance of η as physically based parameter for the correct modeling of the behaviour of liquefied sandy soils.

Keywords: Apparent viscosity; liquefied soils; 1D non-linear site response analysis.

1. Introduction

The complete loss of soil strength and stiffness, which occurs during earthquake-induced liquefaction in loose saturated sandy soil deposits, marks a change of state of the soil, that switches from solid to liquid. The transformation of soil into a liquid state is generally responsible of serious damage to engineering structures. Studying in depth the behaviour of liquefied sands results extremely important from a technical point of view in order to predict the permanent displacements of soils and the subsidence of the built areas (Nishimura et al., 2002). When liquefaction occurs, the framework of soil mechanics cannot be adopted and soil behaviour should be studied using a fluid mechanics approach.

Hamada and Wakamatsu (1998) proposed to study the behaviour of liquefied soils as a pseudo-plastic fluid through the following equation:

$$\eta = \frac{\tau}{\dot{\gamma}} = k \cdot (\dot{\gamma})^{(n-1)} \tag{1}$$

Where η is the viscosity of the fluid and k and n are the fluid consistency coefficient and liquidity index, respectively (Zhou et al., 2014). Obviously, the two parameters k and n depend on the kind of fluid. As reported by Zhou et al. (2014) k can reflect the consistency of fluid and it shows the fluidity of fluid. On the other hand, n can reflect the nature of the fluid. A Newtonian fluid has n=1. When n<1, the fluid is shear a thinning flow, when n>1, the fluid is a shear thickening flow.

The pseudo-plastic behaviour of liquefied soils was demonstrated by the experimental results of Chen et al., (2006) and proposed a flow constitutive model, which was implemented into the finite -difference algorithm FLAC3D (Chen et al. 2011) to reproduce the flow deformation process induced by soil liquefaction. Chen et al., (2016) proposed to compute η in each loading cycle of undrained tests (η_i) as an apparent viscosity defined as:

$$\eta_i = \frac{\tau_{i,max} - \tau_{i,min}}{\dot{\gamma}_{i,max} - \dot{\gamma}_{i,min}} \tag{2}$$

where τ_{max} and τ_{min} are the maximum and minimum values of the applied cyclic shear stress and $\dot{\gamma}_{max}$ and $\dot{\gamma}_{min}$ are the shear strain rates. The potentiality of this parameter to study the behaviour of liquefiable sandy soils has been already highlighted by Lirer & Mele (2019), Lirer et al. (2020) and Mele (2022). In Figure 1a, the expected trend of the apparent viscosity with the number of cycles (N_{cyc}) has been reported:

For $N_{cyc} = 0$, the initial value of η is called η_0. When the soil has a solid phase the value of η is almost constant: after that, the apparent viscosity decreases suddenly. It is a transition phase, where two phases (solid and liquid) coexist. When liquefaction has fully developed, the soil becomes liquid and a minimum single value of apparent viscosity should be expected. The value of the apparent viscosity of a liquefied soil may be identified by η_{fluid}. In other words, the liquefaction is attained in correspondence of the elbow of the η - N_{cyc} decay law, before attaining η_{fluid}, where the complete state change occurs. Liquefaction triggering can be clearly identified plotting the experimental results in the plane $\Delta\eta/\eta$ - N_{cyc}, where $\Delta\eta/\eta$ is evaluated as $(\eta_i-\eta_{i+1})/\eta_i$ where i is the generical loading cycle. The relationship may be described by a sort of bell-shaped curve, whose maximum represents the drop of the apparent viscosity and then the change of state, from solid to liquid (Fig. 1b). Generally, the peak is coincident with the attainment of r_u=0.90 (r_u=pore pressure ratio), which is traditionally the stress parameter adopted to identify the liquefaction triggering (Ishihara, 1993).

The framework of soil mechanics can be adopted up to the transition phase ($\eta<\eta_{trans}$, Fig. 1a) because the soil persists in its original solid state. In the transition phase ($\eta_{trans}<\eta<\eta_{fluid}$) the change of state happens, and then the soil should be studied using a fluid mechanics approach, such as the pseudo-plastic rheological model (eq. 1).

Mele (2022), processing more than 40 cyclic triaxial tests carried out on 6 different sandy soils, confirmed that a power law function (eq. 1) exists between the apparent viscosity (η) and the shear strain rate ($\dot{\gamma}$).

In order to use eq. (1) for liquefied soils, it is important to correctly calibrate the two parameters (k and n). Mele (2022) showed that k seems to be dependent on the cyclic stress ratio (CSR) defined as the ratio between the shear stress (τ) and the effective vertical stress (σ'_v) (Fig. 2a). Regarding the liquid index (n), it should reflect the nature of the fluid. Mele (2022) showed that it is always less than 1 (shear thinning flow) and seems to be mainly affected by k (Fig. 2b).

The strict dependence of k and n can lead to important advantages in the calibration of pseudo-plastic models, allowing to simplify the calibration procedures, implying the calibration of only one parameter (k).

In this paper the correlations (Fig. 2) proposed by Mele (2022) will be validated at full scale, by using the results of 1D non-linear site response analysis of the case study of Treasure Island (California), affected by extensive liquefaction phenomena during the 1989 earthquake.

2. The case study of Treasure Island (California)

Treasure Island is a 400-acre man-made island immediately northwest of the Yerba Buena Island, a rock outcrop in San Francisco Bay. During the 1989 Loma Prieta earthquake, the island was affected by liquefaction phenomena and other liquefaction-related phenomena (sand boils and lateral spreading) (Hanks & Brady, 1991). The soils at Treasure Island may be grouped into four broad categories: the fill material (hydraulic fill) until 13 m from ground surface, recent bay sediments (Young Bay Mud) from 13 to 28.8 m, native shoal sands (fine to medium sand) from 28.8 to 41.2 m and older bay sediments (old Bay Clay) from 41.2 to 88m, at which the bedrock was assumed (Fig. 3a), based on the Vs profile reported by Grazier (2011) (Fig. 3b). The ground water table is at 4 m from ground surface.

Mele et al. (2022) performed a 1D non-linear site response analysis in effective stresses for this site by using DEEPSOIL code (Hashash et al., 2020). For the sake of simplicity, shear modulus degradation and damping curves have been defined grouping the sand formations (hydraulic fill and sand layers) and the clayey formations (young and old clay bay). The upper bound curves proposed by Seed and Idriss (1970) have been assumed for sandy layers (Fig. 3c), while the curves obtained by laboratory tests on young bay mud samples by Hryciw et al. (1991) have been used for the clayey formations (Fig. 3c), as reported by Chiaradonna et al. (2019). The bedrock has been modelled in DEEPSOIL as an elastic half-space with total unit weight of 25 kN/m^3 and V_s of 2430 m/s. The input motion, applied at the base of the model, is the EW component of the acceleration record at Yerba Buena Island (Fig. 3d).

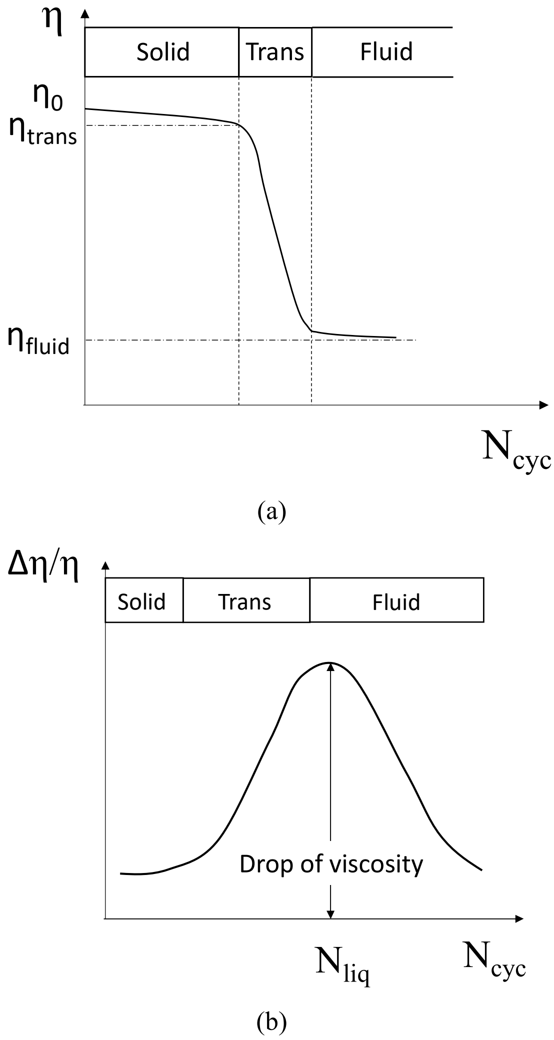

Figure 1. Trend of the apparent viscosity η (modified from Mele et al., 2019), with number of loading cycles (N_{cyc}) (a) and $\Delta\eta/\eta$ with N_{cyc} (Mele et al., 2023) (b).

The generation of pore pressure has been simulated by using the energy-based model of Berrill & Davis (1985). Further details of the performed analysis may be found in Mele et al. (2022).

In Figure 4 the excess pore pressure ratio (r_u=$\Delta u/\sigma'_v$) profile has been reported. It can be clearly noted that liquefaction occurs in the hydraulic fill (r_u=0.90) in two layers located at different depths: 6.75 – 7.75 m and 10.8 – 12.8 m.

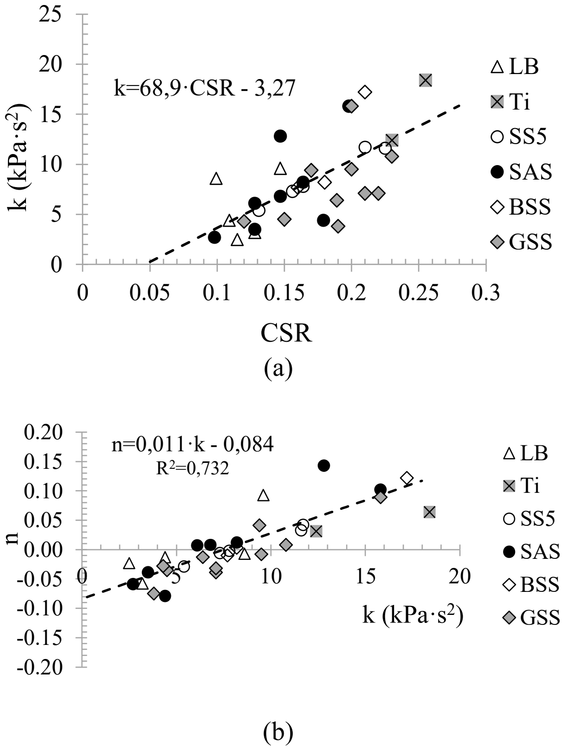

Figure 2. Fluid consistent coefficient (k) versus CSR (a) and linear relationship between k and n (b) (Mele, 2022). (Sandy soils: LB=Leighton Buzzard; Ti=Ticino; SS5=silica sand N°5; SAS=Sant'Agostino; BSS=brown silty sand from Pieve di Cento; GSS= grey silty sand from Pieve di Cento).

2.1. The apparent viscosity of Treasure Island site

In order to confirm the correlation proposed by Mele (2022) - showed in Figs. 2 - and highlight the potentiality of the apparent viscosity to study the behaviour of liquefied soils, the results of the one-dimensional dynamic analysis performed by Mele et al. (2022) have been processed according to a viscous perspective.

Four depths (z =5.25, 7.25, 8.98 and 11.8 meters from ground surface) have been analyzed in detail. In the shallowest one, no liquefaction occurs as shown by the value of $r_{u,max}$ (=0.63) lower than 0.90 (Fig. 4). Lower r_u than the threshold has been also noted about 9 m. On the contrary, the layers located at 7.25 and 11.8 m attained the liquefaction, as demonstrated by the values of $r_{u,max}$ (Fig. 4).

The apparent viscosity has been computed for the considered four depths via eq. (2), by using the time histories of τ and γ, returned by DEEPSOIL. The maximi and minimi values of τ and γ have been evaluated in each second, not being possible to define a cycle due to the irregularity of the input (Fig. 3d).

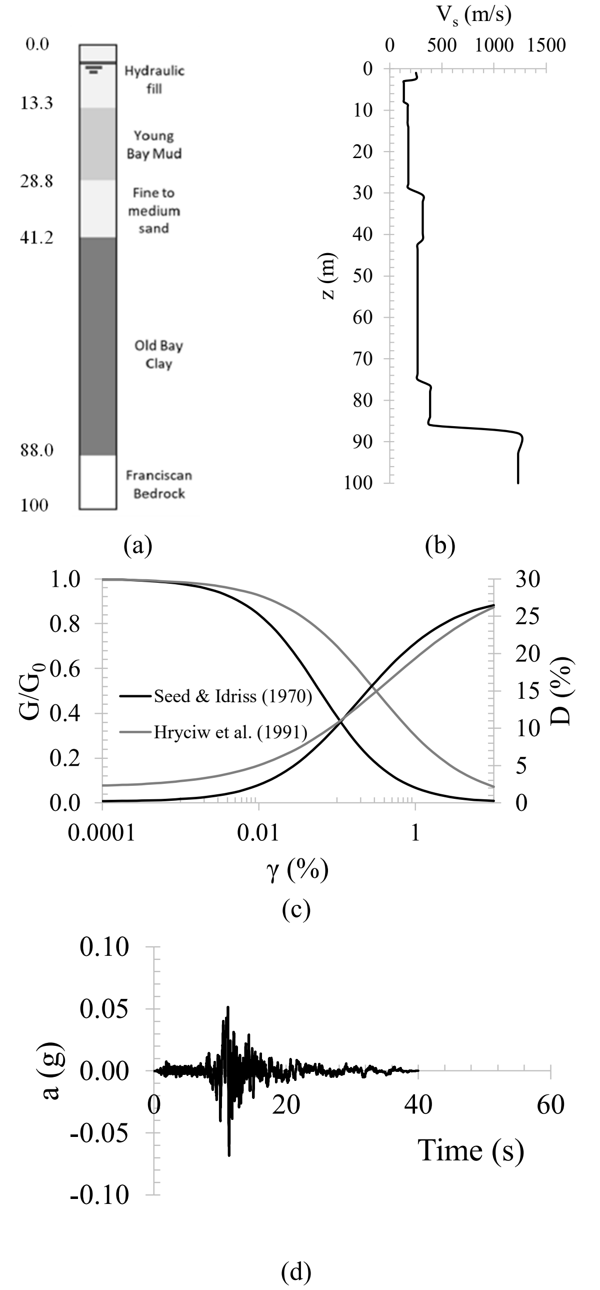

Figure 3. Treasure Island site: stratigraphy column (a), V_s profile (b), normalized shear modulus and damping curves (c) and input motion (d) (Mele et al., 2022).

The decay laws of the apparent viscosity η - time for the considered four depths (z= 5.25, 7.25, 8.98 and 11.8 m) have been reported in Figure 5. A constant value of the apparent viscosity can be noted for the shallowest layer (z=5.25m) and the middle one (z=8.98m), where liquefaction is not attained (Fig. 5a, c). As expected, the drop of η does not occur because the state of the soil does not change. On the contrary, the layer at which liquefaction occurs (z= 7.25 and 11.8m) exhibit a decay curve (Fig. 5b, d) of the apparent viscosity similar to the theoretical one (Fig. 1), with a very small transition phase. Indeed, a sudden drop of η in correspondence of t=10s occurs. The value of η_0 ranges between 1200 – 2000 kPa·s, highlighting the dependence of η_0 on the effective confining stress, as also reported by Mele (2022).

In the following the results relative to liquefaction triggering and pseudo-plastic behaviour of liquefied soils achieved from the dynamic analyses have been shown and discussed.

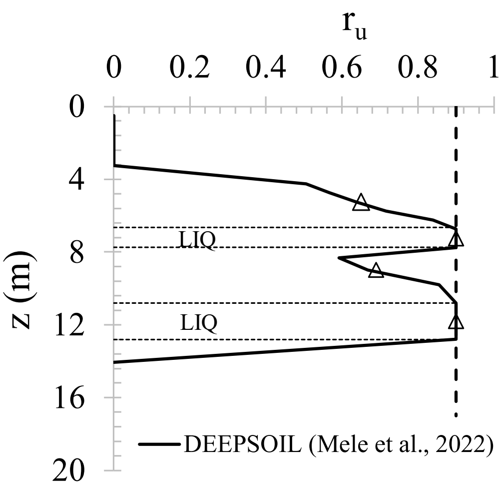

Figure 4. Treasure Island site: excess pore pressure ratio profile (modified from Mele et al., 2022). Triangles indicate the analysed depths.

2.1.1 Liquefaction triggering

In order to evaluate the attainment of liquefaction by means of a viscous criterion, $\Delta\eta/\eta$ – time has been plotted together with r_u for each considered layer (Figs. 6). It is worth noting that, although a strong scatter of data is evident, a peak of $\Delta\eta/\eta$ has not been reached at 5.25m (Fig. 6a) and 8.98 m (Fig. 6c), on the contrary, a maximum value of $\Delta\eta/\eta$ is clear in the deepest layers (Figs. 6b, d), reached around 10 s, when r_u attains 0.90 and the drop of η occurs (Figs. 5b, d).

The results confirm, once again, that the drop of viscosity marks the change of state of soil from solid to liquid, allowing to identify liquefaction correctly.

2.1.2 Pseudo-plastic behaviour of liquefied soils

In Figure 7 the results of the dynamic analysis performed with DEEPSOIL in terms of η-$\dot{\gamma}$ have been plotted for the four different depths already shown in the previous sections (z=5.25 m, 7.25 m, 8.98 m and 11.8 m, in Fig. 7 a, b, c and d, respectively as shown in Fig. 4). It can be noted that, the results confirm that the two variables are linked by a power law (eq. 1), even though at depths of 5.25 and 8.98 m the functions are not completely explicated due to the fact that the soil does not attain liquefaction, so a change of state of the soil does not occur.

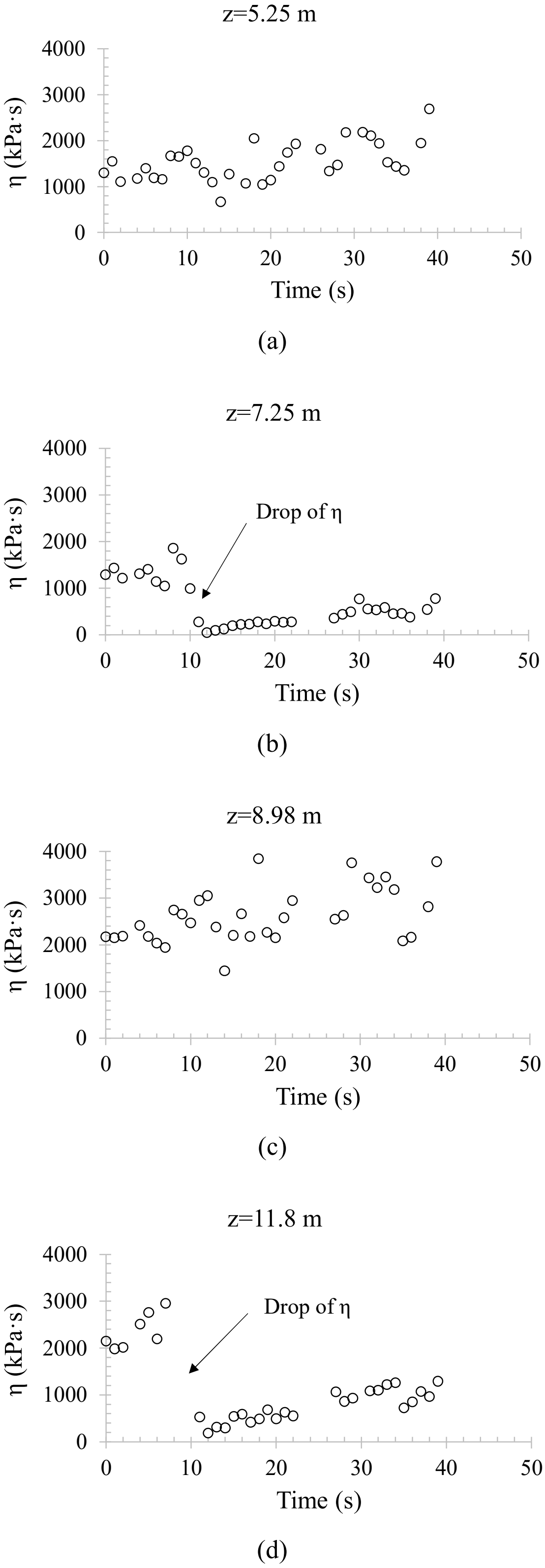

Figure 5. Decay laws of the apparent viscosity at 5.25 m (a), 7.25 m (b), 8.98 (c) and 11.8 m (d) from ground surface of Treasure Island site.

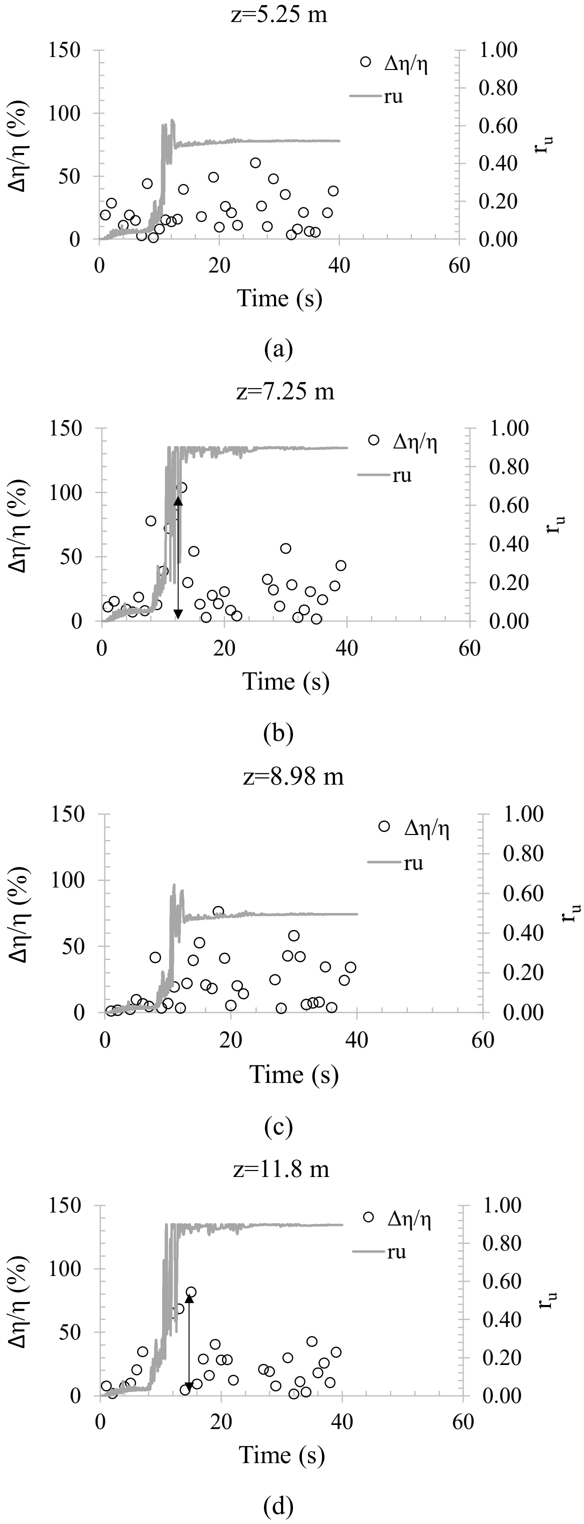

Figure 6. Comparisons between Δη/η and r_u versus time at 5.25 m (a), 7.25 m (b), 8.98 (c) and 11.8 m (d) from ground surface.

In the same figures, the prediction curve obtained by adopting the relationships proposed by Mele (2022) for the quantification of k and n (Figs. 2) has been plotted. As previously mentioned, knowing the capacity of the soil (CSR), which may be found easily from the simple procedure proposed by Seed & Idriss (1971) ($CSR=0.65 \cdot \tau_{max}/\sigma'_v$), a value of the fluid consistency coefficient k may be estimated (Fig. 2a) at each depth. In Figure 8 CSR profile has been plotted in the shallowest layer (from 0 to 13 m). Moreover, in Table 1, CSR of the four examined layers have been summarized. As described above, from CSR the parameters k and n of eq. (1) can be easily estimated by means of linear correlations (Figs. 2).

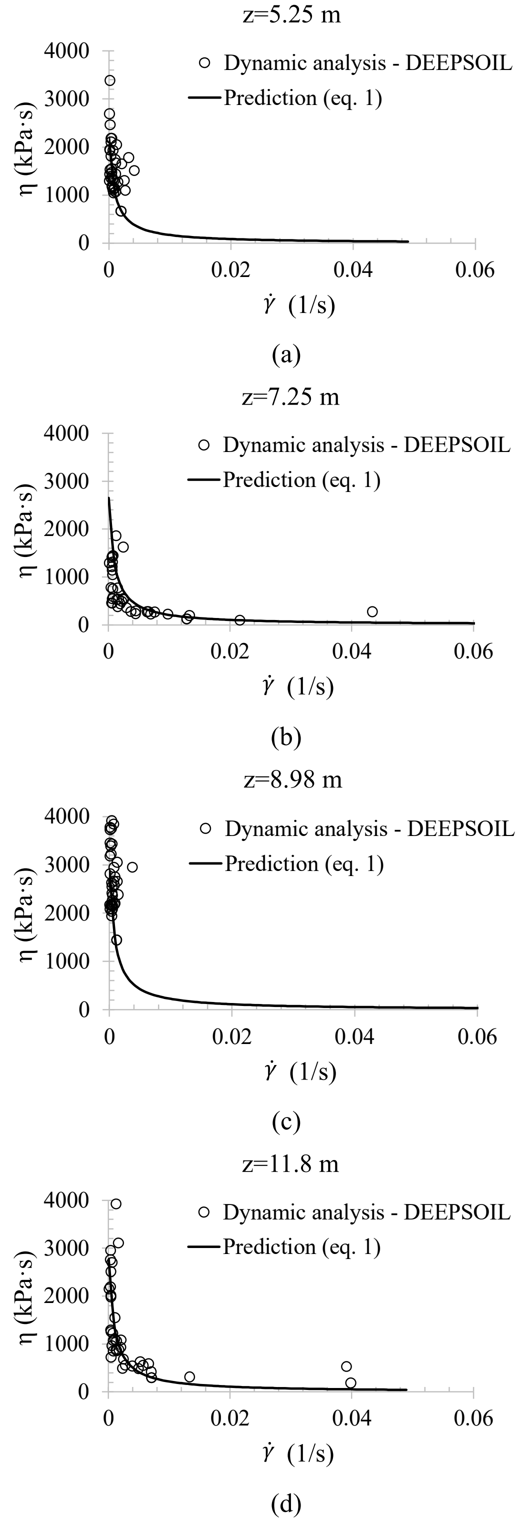

Figure 7. Results of dynamic analysis in terms of η-γ˙ compared with those predicted by the proposed method at 5.25 m (a), 7.25 m (b), 8.98 m (c) and 11.8 m (c) from ground surface.

The values of k and n parameters adopted to predict the η-$\dot{\gamma}$ relationships at the four depths have been reported in Table 1.

The estimated values of k and n through the proposed correlations (Figs. 2) seem to fit well the results obtained by performing a dynamic analysis. Also, at 5.25 and 8.98 m, even though liquefaction does not occur, the results of the dynamic analysis seem to tend towards the simulated curves η-$\dot{\gamma}$.

The knowledge of CSR seems to be enough to estimate the values of k and n and consequently, to model the behaviour of liquefied soils through a pseudo-plastic rheological model.

The correct modelling of the behaviour of liquefied soils may be an important tool in prediction of the permanent displacements of soils and the subsidence of the building.

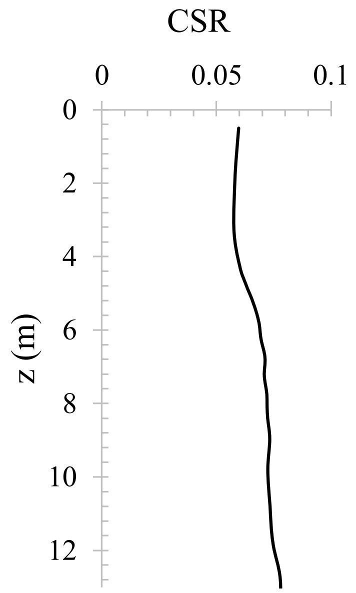

Figure 8. CSR profile of Treasure Island site.

Table 1. Calibrated parameters for pseudo-plastic behaviour of liquefied soils for Treasure Island site.

Depth (m)	CSR	k (kPa·s^2)	n
5.25	0.0661	1.36	-0.0689
7.25	0.0709	1.69	-0.0652
8.98	0.0732	1.85	-0.0634
11.8	0.0723	1.78	-0.0641

3. Conclusions

It is well-known that the framework of soil mechanics cannot be adopted to reproduce the behaviour of liquefied sands, due to the fact that when effective stresses are nihil, a change of state of the soil occurs from solid to liquid. Therefore, the soil behaviour of liquefied sands should be studied using a fluid mechanics approach. In this paper the potentiality of the apparent viscosity (η) as a parameter to study the behaviour of liquefied soils as non-Newtonian fluids is discussed. The results of a 1D non-linear analysis performed in effective stresses of the case study of Treasure Island (California) have been interpreted from a viscous perspective. Two main conclusions drawn from this research are described as follows:

1) When liquefaction occurs a clear peak in the plane time - $\Delta\eta/\eta$ can be clearly identified, which corresponds to the attainment of r_u=0.90.

2) The correlations proposed by Mele (2022) to calibrate the parameters (k and n) of the pseudo-plastic law (eq. 1) have been validated. Known CSR, k and n may be easily estimated. The good agreement of the predicted law with the results obtained from the dynamic analysis states the reliability of the proposed correlations.

The knowledge of k and n allows to predict the pseudo-plastic behaviour of liquefiable sandy soils (eq. 1) and then to model their behaviour when the effective stresses are nihil.

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