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# Experimental and conceptual evidence about the limitations of shear wave velocity to predict liquefaction

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ABSTRACT

Based on the liquefaction performance of sites with seismic activity, the normalized shear wave velocity, $V_{s1}$, has been proposed as a field parameter for liquefaction prediction. Because shear wave velocity, $V_s$, can be measured in the field with less effort and difficulty than other field tests, its use by practitioners is highly attractive. However, considering that its measurement is associated with small strain levels, of the order of $10^{-4}$–$10^{-3}$%, $V_s$ reflects the elastic stiffness of a granular material, hence, it is mainly affected by soil type, confining pressure and soil density, but it is insensitive to factors such as overconsolidation and pre-shaking, which have a strong influence on the liquefaction resistance. Therefore, without taking account of the important factors mentioned above, the correlation between shear wave velocity and liquefaction resistance is weak.

In this paper, laboratory test results are presented in order to demonstrate the significant way in which OCR (overconsolidation ratio) affects both shear wave velocity and liquefaction resistance. While $V_s$ is insensitive to OCR, the liquefaction resistance increases significantly with OCR. In addition, the experimental results also confirm that $V_s$ correlates linearly with void ratio, regardless of the maximum and minimum void ratios, which means that $V_s$ is unable to give information about the relative density. Therefore, if shear wave velocity is used to predict liquefaction potential, it is recommended that the limitations presented in this paper be taken into account.

## 1. Introduction

Earthquakes of medium-to-large magnitude have systematically induced liquefaction in areas with sandy soil deposits. Recently, earthquakes in Chile 2010 (Mw=8.8), Japan 2011 (Mw=9.0) and New Zealand 2011 (Mw=6.3) have induced liquefaction of sands in many areas. As a consequence, these countries have had to manage the extensive damage of buildings, ports, dams, routes, lifelines, and bridges, along with the significant human and economic cost resulting from seismic events.

The state of the art and practice in geotechnical engineering provide analyses and methodologies to understand liquefaction phenomenon, as well as tools to predict the triggering of liquefaction. However, although the phenomenon is reasonably well understood, liquefaction is still one of the main sources of the large overall economic cost caused by earthquakes. Therefore, every effort should be made to develop new techniques and enhance existing methodologies for analyzing liquefaction, using theoretical and practical approaches. These efforts must account for the inherent difficulties faced on a daily basis by practitioners and researchers.

The assessment of liquefaction potential of loose saturated sandy soil deposits, soils with the highest liquefaction potential, can be done by retrieving "undisturbed" samples for laboratory tests; however, the successful completion of laboratory testing on this kind of soil is not always possible.

To overcome this situation there is a consensus in favor of field testing procedures that have the advantage of addressing the complexity of soils in their natural, undisturbed in-situ conditions.

In this context, the penetration resistances obtained by either Standard Penetration Tests (SPT) or Cone Penetration Tests (CPT), are well-accepted field parameters to characterize sandy soils and formulate significant correlations with the liquefaction resistance [1]. Figs. 1 and 2 present state-of-practice correlations between penetration resistances and cyclic resistances used in liquefaction analysis today.

Alternatively, the normalized shear wave velocity, $V_{s1}$, has been proposed as a field parameter for liquefaction prediction. The chart using $V_{s1}$ is presented in Fig. 3. This chart uses the same framework of liquefaction charts developed based on the liquefaction performance of sites with seismic activities (Dobry et al. [2]; Robertson et al. [3]; Andrus et al. [4–6]; Dobry [7]).

Because the shear wave velocity correlates with the soil density, and because it can be measured in the field in a straightforward way, the $V_s$-

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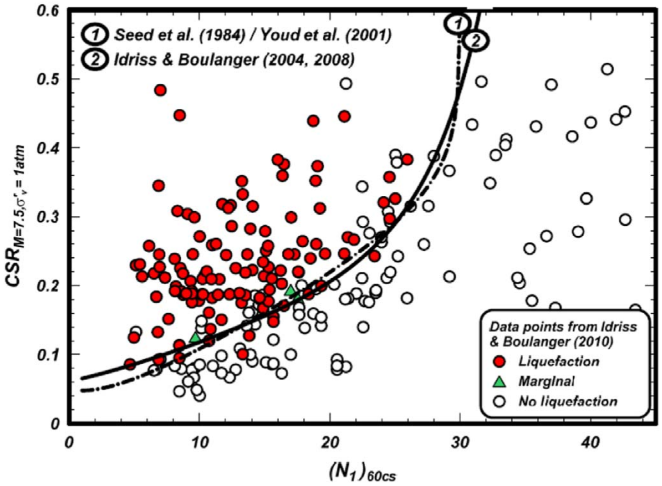

**Fig. 1.** Liquefaction chart based on SPT- $(N_1)_{60\ CS}$, $M_w$=7.5 [31].

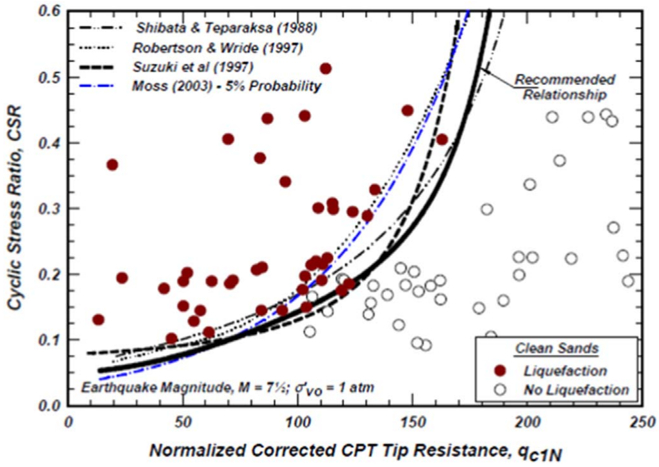

**Fig. 2.** Liquefaction chart based on tip resistance of CPT. $M_w$=7.5 ([41]).

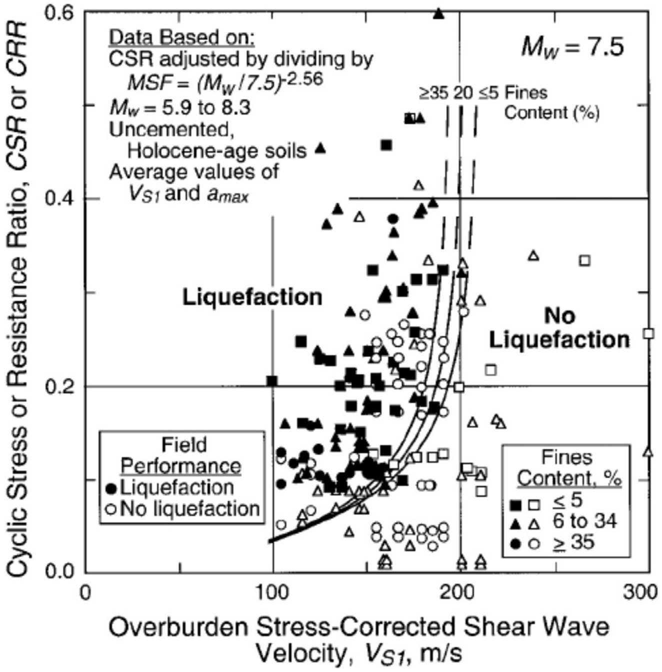

**Fig. 3.** Liquefaction chart based on shear wave velocity. $M_w$=7.5 [5].

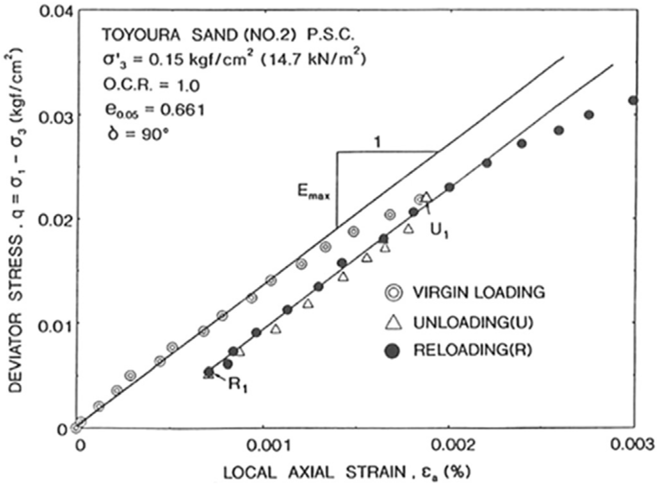

**Fig. 4.** Stress-strain curve showing elastic behavior for axial strain $\leq 10^{-3}$% (shear strain $\leq 1.3\times10^{-3}$%) [10].

based procedures to evaluate liquefaction resistance are of great interest and naturally attractive to geotechnical engineers. Despite its appealing features for engineering practice, there is an important concern that arises in the use of $V_s$ as a liquefaction predictor. The shear wave velocity measurements are associated with small strain levels, of the order of $10^{-4}$–$10^{-3}$%. Therefore, this parameter can only capture elastic soil properties and is unlikely to be sensitive to factors that affect liquefaction, which is a large strain phenomenon (Jamiolkowski et al. [8]; Verdugo, [9]).

Based on this concern, the present paper discusses the intrinsic limitations of the use of the shear wave velocity as a liquefaction predictor.

## 2. Shear strain levels and behavior of sandy soils

Depending on the shear strain level that an element of sandy soil experiences, the mechanical behavior could be significantly different. For shear strains below $10^{-5}$ ($10^{-3}$%), the stress-strain response is fairly linear, as shown by the experimental results obtained by Tatsuoka et al. [10], and presented in Fig. 4. This observation is also supported by the rather limited degradation experienced by the shear modulus of sands in this range of shear strains, as depicted in Fig. 5 (Kokusho [11]).

For shear strains greater than $10^{-5}$ ($10^{-3}$%), sandy soils show an elasto-plastic behavior, where both permanent and recoverable mechanical strains are observed after unloading. In this scenario, plastic deformations take place, even though no volumetric strain accumulations are observed up to a strain level of the order of $10^{-4}$ ($10^{-2}$%).

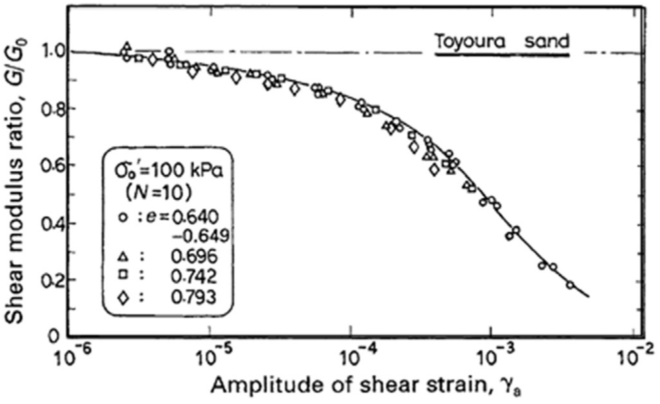

**Fig. 5.** Typical degradation curves of shear modulus for Toyoura sand [11].