Influence of the lateral spreading on the seismic dilatometer (SDMT) parameters: a case study in Christchurch, New Zealand

S Amoroso [i], Paola Monaco [ii] and Kyle M. Rollins [iii]

i) Associate Professor, Department of Engineering and Geology, University of Chieti-Pescara, Viale Pindaro, 42, 65129 Pescara, Italy;
Research Associate, Istituto Nazionale di Geofisica and Vulcanologia, Italy.
ii) Associate Professor, Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila,
Piazzale Ernesto Pontieri 1 – Monteluco di Roio, 67100 L'Aquila, Italy.
iii) Full Professor, Department of Civil Environmental Engineering, Brigham Young University, 430 EB, Provo, UT 84602, USA.

ABSTRACT

The use of "simplified procedures" for the study of lateral spreading could be misleading, and it is debatable whether or not lateral spreading case histories should be included in liquefaction triggering databases. In this context, the 2010-2011 Canterbury Earthquake Sequence (CES) provides several examples of liquefaction and lateral spreading, as identified by the post-earthquake reconnaissance campaigns. Major to moderate lateral spread displacements were observed in the proximity of the Avon River in Christchurch (New Zealand), within about 100-200 m from the fluvial axis and with maximum crack widths of over 200 mm. This paper documents the results of a series of seismic dilatometer tests (SDMT) performed along a section that crosses the Wainoni suburb from the Avon River, where lateral spreading was severe, to farther from the river, where liquefaction features were relatively minor during the CES. Profiles of the SDMT parameters, especially of the horizontal stress index (K_D), show significantly higher values when the sounding is close to the river but insignificant changes at greater distances from the river. Increases in K_D may be related to an increase in the lateral stress in the subsoil induced by compression of the lateral spread mass near the river. Because the flat dilatometer test (DMT) is more sensitive to changes in lateral stress than other in-situ tests, this increase in lateral stress during lateral spreading may not have been recognized using other test methods. Although post-liquefaction in-situ testing is commonly used to develop liquefaction triggering databases, the observed increase in K_D suggests that the DMT-based triggering curves should only include post-liquefaction case histories with no lateral spreading. Similar precautions may be necessary for other in-situ tests after additional research.

Keywords: flat dilatometer test, lateral spreading, horizontal stress index, Canterbury earthquake sequence, liquefaction assessment

1 INTRODUCTION

Earthquakes and related coseismic effects at the surface, such as liquefaction and lateral spreading, can impact humans due to the resulting economic or social disruptions (e.g., slope and foundation failures, flotation of buried structures, etc.). Therefore, it is necessary to have reliable liquefaction assessment procedures to predict this hazard. The use of "simplified procedures" for the study of lateral spreading could be misleading. As observed by Green et al. (2014), among others, it is debatable whether or not lateral spreading case histories should be included in liquefaction triggering databases. The interpretation of these case histories is often more difficult than level ground liquefaction cases, and require more extensive in-situ test data than is often performed.

In this context, the 2010-2011 Canterbury Earthquake Sequence (CES), New Zealand, provides several examples of liquefaction and lateral spreading, as identified by the post-earthquake reconnaissance campaigns (e.g., van Ballegooy et al. 2014). This paper focuses on the data obtained from seismic dilatometer tests (SDMT) performed along a section that crosses the Wainoni suburb, Christchurch, from the Avon River, where lateral spreading was severe, to farther from the river, where liquefaction features were relatively minor during the CES (Canterbury Geotechnical Database 2013). The results shown in this paper provide insights regarding the appropriate use of liquefaction triggering curves based on data from flat dilatometer tests (DMT) in areas affected or not affected by lateral spreading.

2 SITE INVESTIGATION BY SDMT IN CHRISTCHURCH (NEW ZEALAND)

The seismic dilatometer (SDMT) is the combination of the flat dilatometer (DMT) introduced by Marchetti (1980) with an add-on seismic module for measuring the shear wave velocity V_S (Marchetti et al. 2008).

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Fig. 1. Map of the observed cracks following the February 2011 seismic event in the area of study (Canterbury Geotechnical Database 2013). The map also shows the location of the SDMTs performed for the present study and the trace of the analyzed section.

In December 2013, a SDMT site investigation was conducted in Christchurch, New Zealand, within the scope of the Ground Improvement Trials Project (Earthquake Commission 2013) for New Zealand Authorities (EQC, MBIE, NEES), and United States National Science Foundation (NSF). Among the goals of the SDMT campaign there was the need to increase the DMT liquefaction case history database and to update the related triggering curve. Two years later, in November 2015, additional SDMTs were carried out to investigate some peculiar aspects highlighted through the 2013 site investigation (Amoroso et al. 2015), thanks to the support of the NSF and the Italian Civil Protection Department (DPC). One of the aims of this supplementary campaign was to evaluate the influence of lateral spreading on DMT parameters.

The present study illustrates the SDMT results obtained in the Wainoni suburb along a section within a distance of 500 m from the Avon River, as shown in Fig. 1. SDMT1 and SDMT4 were performed in 2013, while SDMTE, SDMTF, SDMTG and SDMTH belong to the 2015 site investigation. As reported in the Canterbury Geotechnical Database (2013), major to moderate lateral spread displacements, often with ejected material and with maximum crack widths of over 200 mm, were observed within about 100-200 m from the river banks following the M_w 6.2 February 2011 earthquake (Fig. 1). Farther from the river, minor to large liquefaction features were detected following the same seismic event, with occasional indications of "unclassified cracks".

3 INFLUENCE OF LATERAL SPREADING ON THE SDMT PARAMETERS

The SDMT results were used to characterize the sands and silty sands of the upper 10 m depth in the area of study. In Fig. 2 the results are plotted along the A-A' section (trace in Fig. 1) in terms of the horizontal stress index (K_D). This parameter (Marchetti 1980) is obtained from the first DMT pressure reading (p_0), which reflects the horizontal stress acting against the probe during penetration, normalized to the effective overburden stress and can be regarded as an "amplified" in-situ earth pressure coefficient (K_0). K_D can be related to a number of factors (i.e., stress history, pre-straining/aging, microstructure) which are known to influence liquefaction resistance and are difficult to sense by other tests (Monaco et al. 2005). The K_D profiles clearly show higher values, more pronounced in the first 5-6 m of depth (up to an elevation of about – 4 m a.s.l.), near the Avon River (SDMTE K_D approximately up to 15, SDMT1 and SDMT4 K_D approximately up to 10) in gently sloping ground. In contrast, the K_D values, generally lower than 10, drastically decrease below the surficial crust (minimum K_D values ≈ 3-4) and the cracks decrease in width or disappear (SDMTF and SDMTG) as the ground surface flattens further from the river.

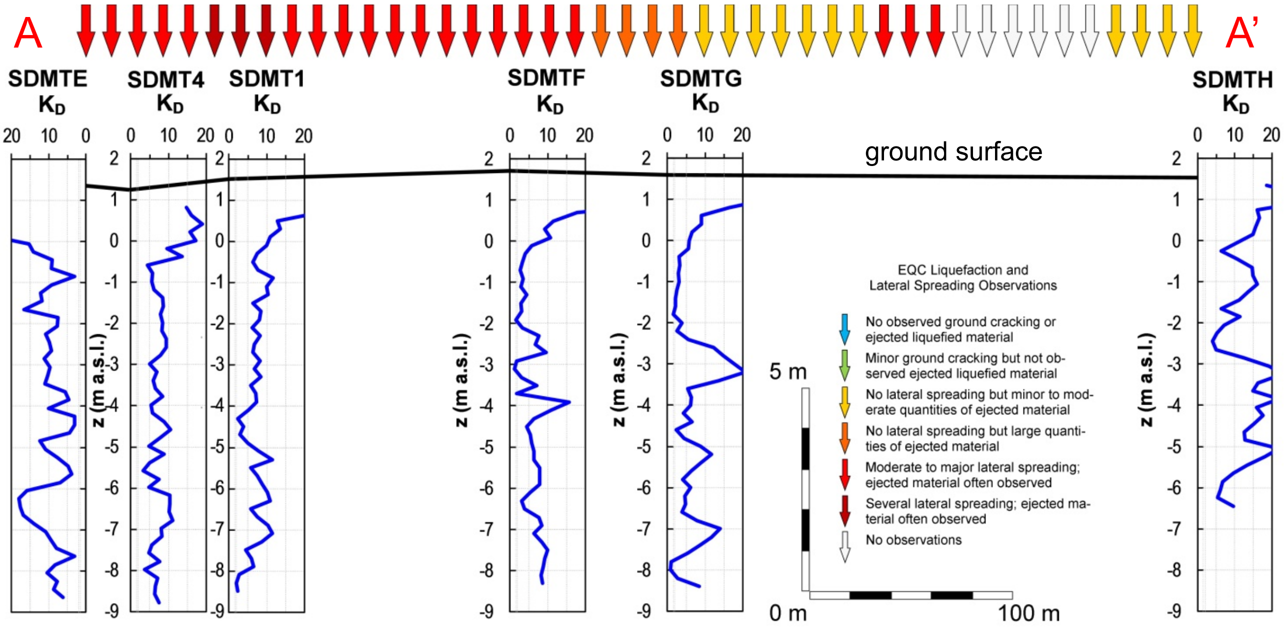

Fig. 2. K_D profiles from the SDMTs performed along the A-A' section together with the liquefaction and lateral spreading observations reported in the Canterbury Geotechnical Database (2013).

These observations suggest that increases in K_D may be related to an increase in the lateral stress in the subsoil induced by compression of the lateral spread mass near the river banks. Because the DMT is more sensitive to changes in lateral stress than other in-situ tests, this increase in horizontal stress due to lateral spreading may not have been recognized using other test methods. In this respect, the post-earthquake SDMT results, especially in terms of K_D, may exhibit higher values when the sounding is close to the river bank, in comparison with SDMTs performed at greater distances from the river. This finding suggests that, in similar cases, the K_D profiles from SDMT could be used to "screen" for lateral pressure increases due to lateral spreading effects along an alignment.

4 LIQUEFACTION ASSESSMENT BY SDMT

With the goal of understanding the influence of K_D increases on the liquefaction susceptibility from DMT triggering curves, liquefaction analyses by simplified K_D-based methods were carried out at the six SDMT locations.

The cyclic stress ratio $CSR_{7.5}$ was estimated by Seed and Idriss (1971) formulation. Magnitude scaling factors (MSF) and shear stress reduction coefficients (r_d) were evaluated according to Idriss and Boulanger (2008). The horizontal peak ground acceleration a_{max} was assumed equal to 0.41g for the 22nd February 2011 earthquake (moment magnitude M_w 6.2), in agreement with Bradley and Hughes (2012a, 2012b). The groundwater table levels (GWT) were provided by Tonkin and Taylor Ltd (2013) and the Canterbury Geotechnical Database (2014) and are reported in Table 1 together with the elevation above the sea level (asl) at each SDMT location. The depths of the critical layers, reported in Table 1 for all the SDMT soundings, were estimated applying the Green et al. (2014) procedure to the results of cone penetration tests (CPT) carried out in the proximity of each SDMT, available from the Canterbury Geotechnical Database (2015).

Table 1. Ground surface elevation, groundwater table level and depth of critical layer (Green et al. 2014) at each SDMT test location.

	Elevation (m asl)	GWT (m asl)	Critical layer top / bottom (m asl)
SDMT1	1.51	0.42	0.33 / -0.87
SDMT4	1.22	0.42	0.48 / -0.90
SDMTE	1.35	0.21	-0.30 / -1.80
SDMTF	1.69	-0.04	-0.76 / -1.78
SDMTG	1.60	-0.03	0.00 / -1.26
SDMTH	1.55	0.33	-1.06 / -2.75

The cyclic resistance ratio $CRR_{7.5}$ was derived from SDMT results using correlations with K_D (DMT methods: Monaco et al. 2005, Tsai et al. 2009, Robertson 2012, Marchetti 2016) and with K_D in combination with the normalized cone resistance (DMT+CPT method: Marchetti 2016) from the aforementioned nearby CPTs.

The $CRR_{7.5}$-K_D correlations were corrected for partial saturation using a partial saturation factor (PSF), inferred from compression wave velocity V_P (Tsukamoto et al. 2002). V_P measurements from cross-hole tests are available from the Canterbury Geotechnical Database (2015), and PSF values were evaluated by the Ground Improvement Trials Project (Earthquake Commission 2013). However, the influence of the PSF on the results in the area of study was found

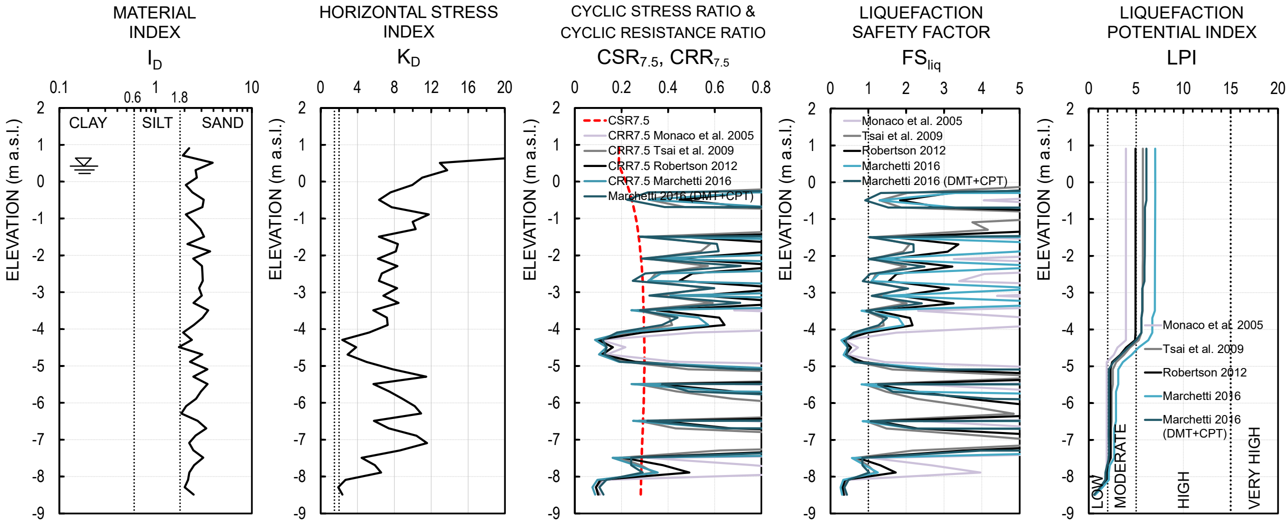

Fig. 3. Liquefaction analyses using different DMT triggering curves in correspondence of SDMT1 (lateral spreading site).

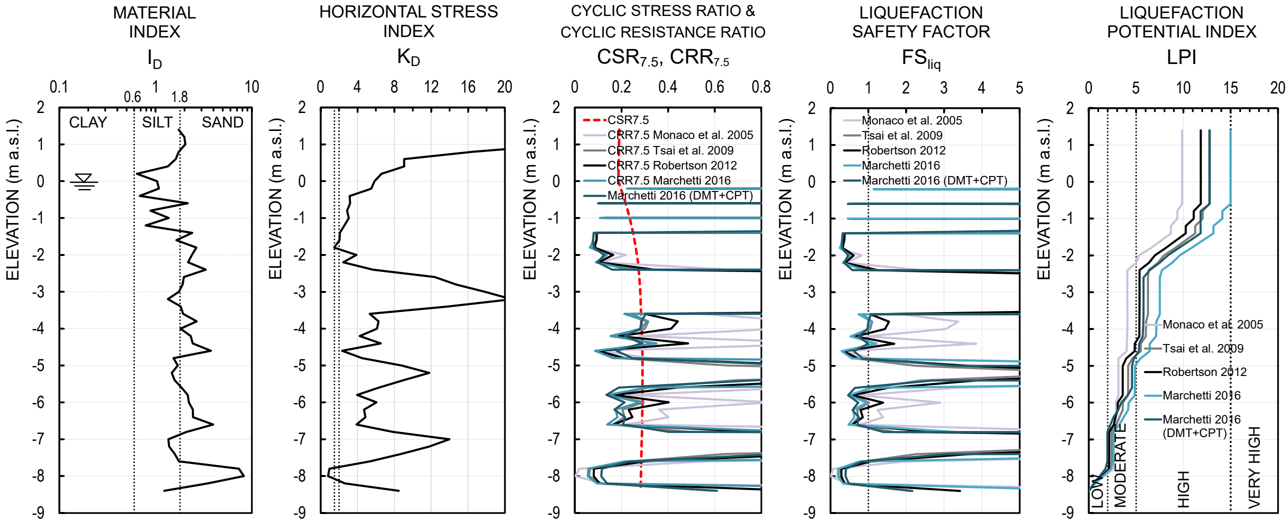

Fig. 4. Liquefaction analyses using different DMT triggering curves in correspondence of SDMTG (no lateral spreading site).

to be negligible.

For conciseness, the results of the liquefaction analyses at one lateral spreading site (i.e., SDMT1) and at one no lateral spreading site (i.e., SDMT G) are illustrated in Figs. 3 and 4, respectively. Each diagram shows the profiles with the absolute elevation of: the material index I_D from DMT (indicative of soil type, Marchetti 1980), the K_D, the $CSR_{7.5}$ compared to $CRR_{7.5}$, the liquefaction safety factor $FS_{liq} = CRR_{7.5}/CSR_{7.5}$, and the liquefaction potential index LPI (Iwasaki et al. 1982) calculated according to the modified form proposed by Sonmez (2003). Despite the SDMT1 profile being entirely composed of sands and silty sands and fully saturated below -0.49 m asl, the shallow layer below the dry crust, the critical layer (from 0.33 to -0.87 m asl, Table 1) is identified as "non-liquefiable" due to the high K_D values, which produce limited LPI values (LPI ≈ 4-7). Therefore, these SDMT tests underestimate the observed liquefaction and lateral spreading damage of the February 2011 event. In contrast, at the SDMTG site the identified critical layer (from 0.00 to -1.26 m asl, Table 1) is identified as liquefiable sandy deposits in relation because of the low K_D values, with LPI values (LPI ≈ 10-15) closer to the liquefaction observations.

Finally, the DMT data pairs $CSR_{7.5}$-K_D related to the selected critical layers were plotted on the DMT liquefaction chart together with the triggering curves used (Fig. 5). The graph clearly highlights that most of the liquefied data points without lateral spreading (SDMTF and SDMTG, in blue) correctly plot on the liquefaction side of the chart, while SDMTH does not match with the available collected post-earthquake observations showing high K_D values, possibly related to the counterslope along the A-A' section (Fig. 2). The lateral spreading data points (SDMT1, SDMT4 and SDMTE, in red) fall in the no-liquefaction area of the chart.

This underlines that, although post-liquefaction in-situ tests are commonly used to develop liquefaction case history databases, the observed increase in K_D due to lateral spreading suggests that the DMT-based triggering curves should only include post-liquefaction case histories with no lateral spreading. Similar precautions may be necessary for other in-situ tests after additional research.

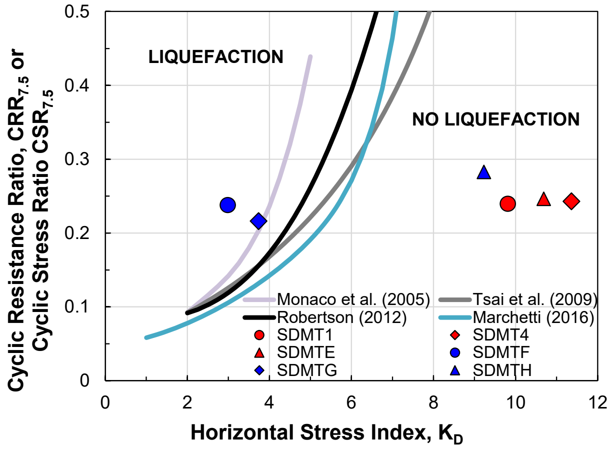

Fig. 5. DMT triggering curves superimposed to the liquefied no-lateral spreading (in blue) and lateral spreading (in red) data points from the analyzed SDMTs.

5 CONCLUSIONS

The Canterbury Earthquake Sequence (CES) and the related liquefaction and lateral spreading case history database offer a valuable opportunity for the update of the triggering curves by in-situ tests. In particular, the in-depth site investigation by seismic dilatometer (SDMT) in the proximity of the Avon River in Christchurch (New Zealand), an area strongly affected by liquefaction and lateral spreading phenomena according to the Canterbury Geotechnical Database (2013), helped to detect that the increase in the horizontal stress index (K_D) is probably due to compression of the lateral spread mass near the river banks. This result is particularly relevant for the improvement of the existing $CRR_{7.5}$-K_D correlations. Based on the above observations, the DMT-based triggering curves should only include post-liquefaction case histories with no lateral spreading. Similar precautions may be necessary for other in-situ tests after additional research.

Further research may be realized in the future performing additional SDMTs in different horizontal directions to verify the existence of a greater horizontal stress in the direction of the lateral spreading.

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