

USING THE MARCHETTI DILATOMETER TO DETERMINE SOIL STIFFNESS PARAMETERS

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ABSTRACT: This study explores the transition from laboratory-based to field soil testing, focusing on the Marchetti flat dilatometer and its seismic counterpart for geotechnical applications. The study emphasises the challenges of obtaining undisturbed soil samples in field conditions while highlighting the advantages of integrating field measurements with advanced geotechnical analysis. Utilizing a combination of experimental, observational, and analytical methods, the study assesses soil stiffness parameters, transverse wave velocity, and associated geotechnical properties under both static and dynamic loads. The study's findings underscore the versatility of the dilatometer and its seismic counterpart in characterizing a range of soil types, including those that are over-compacted and very soft. Key applications include foundation settlement prediction, quality control of compaction in road construction, and cyclic liquefaction resistance assessment. The results of the study establish significant correlations between soil parameters, which support sustainable construction practices and efficient soil reclamation in seismically active regions. This research underscores the utility of dilatometer technologies in advancing geotechnical investigations and fostering resilient infrastructure development.

Keywords: Geotechnical Field Testing, Seismic Dilatometer, Liquefaction Resistance, Subsurface Characterization, Soil Properties

1. INTRODUCTION

Field testing plays a critical role in advancing geotechnical research, offering numerous advantages such as speed, cost-effectiveness, reproducibility, and the capacity to generate large datasets. These methods are particularly beneficial when studying sandy soils, where obtaining undisturbed samples proves to be challenging. While laboratory testing remains essential for large-scale projects and foundational research, there is a transformative shift towards field-based methods in geotechnical engineering. A notable advancement in this area is the Marchetti flat dilatometer and its seismic counterpart (SDMT), which have proven particularly valuable in characterising soils in seismically active regions, such as Kazakhstan. The Marchetti dilatometer is capable of assessing a wide range of soil conditions, from very soft to over-compacted soils, providing essential data for seismic design, settlement prediction, and cyclic liquefaction resistance evaluation [1].

The transition from conventional laboratory-based testing to advanced field methods signifies a substantial advancement in soil characterisation. This study underscores the merits of integrating the Marchetti flat dilatometer and SDMT technologies with advanced geotechnical analysis, emphasising the capability to ascertain precise soil stiffness parameters and wave velocity measurements under both static and dynamic loads. The study demonstrates the potential of these technologies to enhance subsurface characterization, especially in regions with complex soil profiles.

A number of studies have contributed to the development of an understanding of the application of tools such as the Marchetti Dilatometer and the SDMT in geotechnical research. For instance, Das et al. explored the use of these tools in Kazakhstan but did not assess their comparative effectiveness against traditional methods or their accuracy in the local context [2]. This omission creates a lacuna in our understanding of how these tools function in specific geotechnical conditions, such as the seismic activity of the region. Similarly, Bai et al. focused on the application of advanced ceramic materials in construction, but their study did not address applications related to soils [3]. This underscores the paucity of research that has linked cutting-edge materials with soil characteristics, a prerequisite for ensuring the durability and stability of infrastructure.

In a related study, Yavorska and Pankiv advanced a set of diagnostic features for soils in the Ukrainian Carpathians. However, their methodology was found to have limited general applicability across different soil types, thus restricting its potential for broader use in diverse regions [4]. This underscores the necessity for the development of more universally applicable approaches that can encompass a range of soil types. Rocha et al. conducted laboratory tests for unsaturated tropical soils, but did not consider alternatives to field tests, which may be more cost-effective and suitable for widespread use in other regions [7]. This also points to the lack of studies comparing laboratory and field methods for specific conditions, particularly in seismically active areas.

The central contribution of this study lies in its

attempt to adapt and apply the principles of the Marchetti dilatometer and the SDMT to the geotechnical conditions of Kazakhstan, thereby expanding the existing knowledge on subsurface characterisation in this region. The integration of seismic wave velocity measurements with traditional dilatometer testing provides a novel approach to the assessment of soil properties in regions characterised by non-subsiding sands and subsiding loams. The study underscores the dilatometer's adaptability in evaluating diverse soil types, ranging from soft to over-compacted soils, and puts forward a framework for seismic design and sustainable infrastructure development in seismically active regions.

This study provides more accurate results than previous research in this field, as it addresses gaps in the understanding of soil characterisation in Kazakhstan's unique geotechnical context. It strengthens the applicability of field-testing methods by incorporating real-world applications such as settlement prediction and liquefaction resistance evaluation. A comparison of these findings with prior research underscores the importance of these technologies in improving the accuracy and reliability of geotechnical data, particularly in seismic regions where conventional testing methods often fall short.

The subsequent sections of this paper will delve into the materials and methods used in this study, describing the experimental design, the application of the Marchetti dilatometer and the SDMT, and the process for deriving key soil parameters. The ensuing presentation of the findings from the field tests will be accompanied by a discussion of the implications for geotechnical engineering and infrastructure development. Finally, the conclusions will summarise the key findings, emphasising the contributions of this study to the field of geotechnical research.

2. RESEARCH SIGNIFICANCE

The significance of this study lies in its exploration of the Marchetti flat dilatometer and its seismic counterpart, which represents a significant advancement for the field of geotechnical engineering. By addressing the challenges associated with subsurface characterisation, the study provides insights into soil behaviour under various conditions. The study's emphasis on innovative testing methods and correlation models enhances the reliability of geotechnical data, aiding in the design and construction of resilient infrastructure. The study's findings contribute to enhancing the accuracy of field tests, particularly in seismic regions, and support sustainable construction practices by advocating efficient, cost-effective methods for soil analysis. This, in turn, paves the way for a wide range of applications in engineering and geology.

3. MATERIALS AND METHODS

This study employed experimental, observational, and measurement methods to assess soil properties using the Marchetti flat dilatometer and the Seismic Dilatometer Marchetti Testing. The experimental design focused on the application of the Marchetti flat dilatometer, which has been used for field soil testing in industrialised countries. Test methods involving this instrument are part of the standards of the American Society for Testing and Materials (ASTM) and the Eurocodes [8,9]. Detailed studies were carried out under the guidance of the TC16 technical committee of the International Society for Soil Mechanics and Geotechnical Engineering [10]. Ongoing standardisation efforts are being conducted by the International Organisation for Standardisation and the European Committee for Standardisation.

The Marchetti dilatometer was used for penetration testing, assessing soil parameters without drilling lead wells. It consists of a steel blade with a flexible membrane connected to a control unit via an electropneumatic cable. The blade was driven into the ground, and the membrane was inflated with gas. Measurements included initial displacement (1.1 mm), and closing pressures, used to derive material index, dilatometer modulus, and lateral pressure coefficient (K_D). These parameters determined deformation modulus (M_{DMT}), non-drained shear strength (c_u), and lateral pressure coefficient at rest (K_0). Seismic wave propagation was evaluated using SDMT, integrating DMT with dual-sensor shear wave velocity (V_s) testing (0.5 m apart).

Measurement methods allowed obtaining both the shear modulus with minor deformations: $G_0 = \rho V_s^2$, where ρ – density of the soil, and stiffness under real loads, which facilitates the selection of curves. Pore pressure measurements provided insights into consolidation and filtration coefficients. "Eurocode 8: Design of structures for earthquake resistance" [11] requires the determination of the velocity of transverse waves V_s in the upper 30 m of soil on all construction sites located in seismically active zones. Data analysis included transforming field measurements into engineering parameters and interpreting these results to understand soil behavior under static and seismic loads. Statistical analyses were conducted to evaluate the reproducibility and reliability of the measured parameters, comparison with reference standards was used. Key outcomes, such as compression modulus and cyclic liquefaction resistance, were cross-referenced with empirical correlations established in prior research.

This integrated approach facilitated a comprehensive assessment of soil properties, supporting the design of engineering structures and soil improvement strategies.

4. RESULTS

Standard field equipment such as penetrometers commonly used for static Cone Penetration Testing (CPT) or borings were used to insert the dilatometer into the soil. The most effective method is to insert the blade using a 20-tonne static sensing unit, which allows achieving productivity of up to 80 m/day.

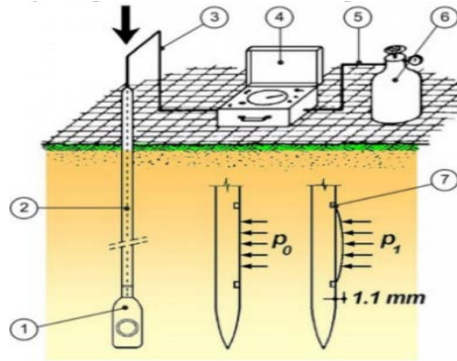


Fig.1 DMT: test scheme [12]

The test begins with inserting a dilatometer into the ground to the required depth. Gas is pumped under the membrane, and after 30 seconds, two pressure values are measured: A (initial expansion pressure) and B (pressure at which the membrane shifts 1.1 mm). Optionally, C (valve closing pressure) can be measured. The blade is then inserted deeper, usually in 20 cm increments (Fig.1). Field measurements are converted into ID (material coefficient), K_D (lateral pressure coefficient), and E_D (modulus of deformation), used to calculate the compression modulus M_{DMT} , shear resistance c_u , and lateral pressure coefficient K_0 for clay soils [10]. Soil density ρ relates to the over-compaction coefficient OCR for clays and friction angle ϕ' for sands. The SDMT combines DMT with a module for measuring

transverse wave velocity [13]. Two sensors, 0.5 m apart, register shear waves, transmitting seismograms to a surface computer.

The velocity of the transverse waves V_s is calculated based on the difference in the distances between the source and the sensors (S_2-S_1) and the time difference between the reception of the signal by the first and second sensor Δt . The reproducibility of the velocity of transverse waves V_s is comparable to the reproducibility of the other four DMT parameters. Field measurements of the velocity of propagation of transverse seismic waves with a Marchetti dilatometer were carried out to determine the seismicity of the site of a construction facility of a residential complex in the Republic of Kazakhstan, Almaty, Medeu district, Khaliullin Street. The geological structure of the area includes deposits of middle-Upper Quaternary age (QII-III), represented by carbonated loams and medium and gravelly sands, overlain by bulk soil and technogenic soils in the form of concrete and asphalt (Tables 1 and 2). According to the results of measurements of the propagation velocities of transverse waves $V_{s,30}$ and $V_{s,10}$ in surface 30- and 10-metre thicknesses in 7 seismic probes, the obtained values are presented in Table 3. The average propagation velocities of transverse waves $V_{s,30}$ and $V_{s,10}$ were calculated in accordance with Eq. (1) and Eq. (2) [11]:

$$V_{s,30} = \frac{30}{\sum_{i=1, N} \frac{h_i}{v_i}} \quad (1)$$

$$V_{s,10} = \frac{10}{\sum_{i=1, N} \frac{h_i}{v_i}} \quad (2)$$

where: h_i – thickness of transverse wave propagation in m/s (with a shear strain level of 10^{-5} or less) for the i -th formation; v_i – velocity of transverse wave propagation in m/s (shear strain level of 10^{-5} or less).

Table 1. Site properties

Age of rocks	Description of soils	Depth of the layer, m		Layer thickness, m
		from	to	
	Soil and vegetation layer	0	0.2	0.2
QIV	Loam of solid to semi-solid consistency, subsiding	0.2	8	7.8
apQII-III	Loam of semi-solid to fluid-plastic consistency, with interlayers and lenses of water-bearing sand, non-subsiding	8	30	22
apQII-III	Sand of medium size, medium density, water-saturated, non-subsiding	28.5	29.5	1

Table 2. Soil properties

Name of the soil	Soil density, g/cm ³			Specific adhesion, kPa			Internal friction angle, degree			Modulus of deformation, MPa	Modulus of deformation, according to stamp tests, MPa
	pn	p'	p''	Cn	C'	C''	φn	φ'	φ''		
Subsiding loam	1.76	1.72	1.73	15/11	13.7	14.4	14/10	12.8	13.3	6.1/3.9	2.6
Non-subsiding loam	2.02	1.97	1.99	7	6.4	6.7	10	9.1	9.6	3.4	20.1
Non-subsiding loam	2.09	2.05	2.06	-	-	-	30	28	30	29.2	

Experimentally determined values of transverse wave propagation velocities in surface 10-metre ($V_{s,10}$) and 30-metre ($V_{s,30}$) soil strata have an average value at a depth of 10 m – 243.96 m/s and at a depth of 30 m – 276 m/s (Fig.2a,b). These variations in wave velocities correlate with soil properties such as density, modulus of deformation (M_{DMT}), and shear strength. Higher V_s values are indicative of denser, non-subsiding soils with greater stiffness, while lower V_s values correspond to softer, less compacted soils. Figure 2 illustrates the relationship between wave velocity and shear modulus (G_0), emphasizing that regions with increased V_s values reflect improved soil stability. According to the requirements of the Code of Rules of the Republic of Kazakhstan ‘Construction in seismic zones,’ the studied ground conditions, characterized by a yield index ($IL \leq 0.5$) and a porosity coefficient $e < 0.9$, belong to type 2 in terms of seismic properties, substantiating the correlation between field-measured wave velocities and soil classification.

Table 3. The velocity of propagation of transverse waves $V_{s,30}$ and $V_{s,10}$ in surface strata of different meters in 7 seismic probes

No. of seismic probe	Average transverse wave velocity (10 m depth), m/sec	Average transverse wave velocity (30 m depth), m/sec
Test-1	249.2	275.1
Test-2	244.3	284.1
Test-3	246.1	270.5
Test-4	230.8	274.3
Test-5	249.4	-
Average	243.9	276

In accordance with the requirements of the Code of Rules of Kazakhstan [14], the average values of $V_{s,30}$ and $V_{s,10}$ m/s and the studied ground conditions according to engineering and geological data with a yield index ($IL \leq 0.5$) with a porosity coefficient $e < 0.9$, they belong to type 2 in terms of seismic properties. Thus, the initial seismicity of the construction area according to the Map (NEO-2475) is equal to 9 points. The specified value of the seismicity of the construction site according to the measured propagation velocities is equal to 9 points. According to the list of Kazakh settlements located in seismic zones, indicating the calculated accelerations α_g for construction sites with different types of ground conditions, in Almaty, the value of the calculated acceleration α_g for a construction site with type 2 ground conditions for seismic properties will be 0.54 g. However, according to the same Code of Rules [14], the value of the calculated vertical acceleration α_{gv} will be 0.48 g. Calculations can be performed for the values of V_s and shear modulus at small deformations G_0 based on three DMT parameters – I_D , K_D , and M_{DMT} [15,16]. Experimental points are formed automatically during each SDMT test [17,18]. The comparison of velocity profiles shown in Fig.3 is a confirmation of the correspondence between the values of V_s obtained using the SDMT method and the values calculated based on K_D , I_D , M_{DMT} . The relative error averages about 20%. In the absence of K_D , there is a slight direct relationship between M_{DMT} and G_0 . M_{DMT} and G_0 represent different parameters. This trend has a significant effect on the compression modulus of deformation M_{DMT} , but not on G_0 . Modules M increase significantly under load, while V_s or G_0 change slightly [19].

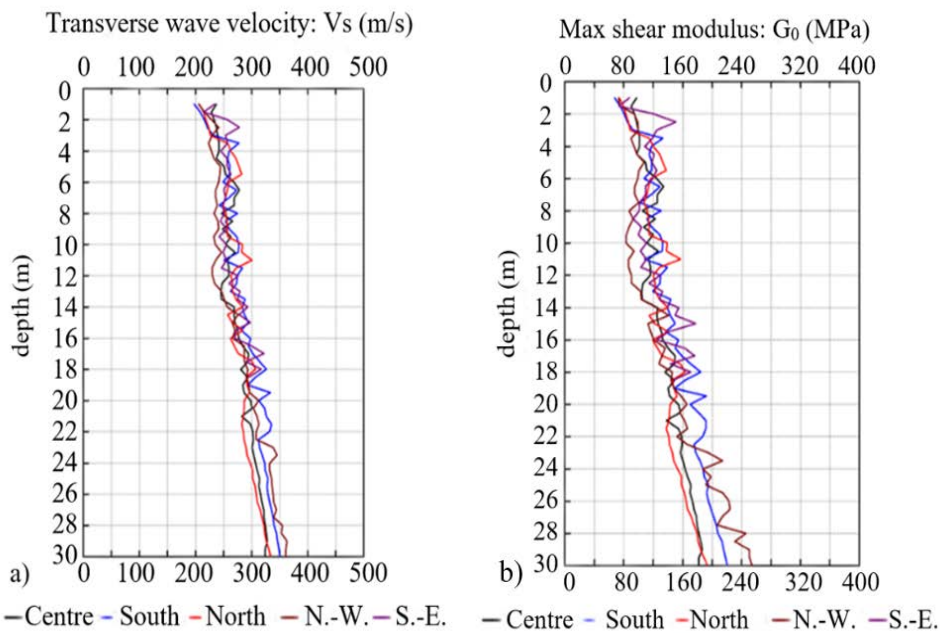


Fig.2a,b Velocity of propagation of transverse waves and shear modulus

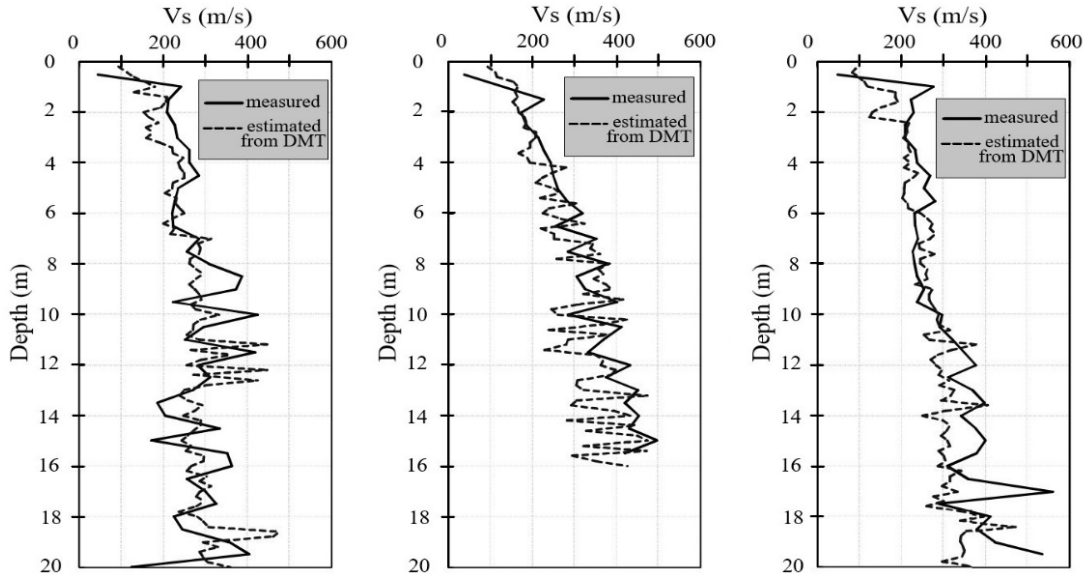


Fig.3 High-speed sections of V_s , Cese di Preturo, Pianola and Royo Piano [17]

Clay rocks can be tested for non-drained cu shear strength in the range from 2 to 1,000 kPa. The range of measured compression modulus of deformation M is from 0.4 to 400 MPa. The dilatometer blade can be embedded using various sounding or drilling rigs. Static sensing installations placed on trucks ensure the most efficient execution of work. Drilling rigs, such as the installation in the “Torpedo” configuration, can be used with some reduction in productivity [10]. In many cases, the results obtained from DMT tests are widely used in conventional engineering and geological calculations to assess the bearing capacity (Fig.4). Predicting the compaction of shallow foundations can be solved using DMT testing. Compaction is calculated using a linear relationship (Eq. (3)) [10]:

$$S_{1-DMT} = \sum \frac{\Delta\sigma_v}{M_{DMT}} \Delta z. \quad (3)$$

$\Delta\sigma_v$ is calculated according to the Boussinesq method, and the compression modulus of deformation M_{DMT} is determined based on the test results by the DMT method. Methods for creating “P-y” curves have been developed based on data obtained from DMT tests [15; 19]. Both approaches provide comparable estimates that fairly accurately reflect the actual behaviour of the soil. The “ $K_D \approx 2$ ” method provides a tool for identifying active or long-past sliding surfaces in over-compacted clays forming slopes [10]. The essence of this method is to identify areas of normally compacted (NC) clay on a slope with an “over-compacted” (OC) profile. The process of determining the NC zones is based on the application of the criterion $K_D \approx 2$. Clay layers that were initially normally compacted, were then deformed and re-compacted.

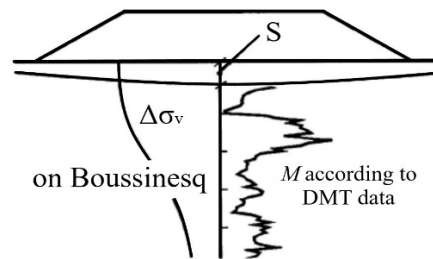


Fig.4 Forecast of settlement S according to DMT test data [20]

DMT tests track artificial soil compaction results, with sealing causing a rapid increase in dilatometric lateral K_D and compression modulus of deformation (M_{DMT}). Robertson et al. note that the M_{DMT} increase is about twice that of q_c [21]. Since compaction aims to reduce settlement, technical characteristics should rely on M_{DMT} rather than relative density. DMT effectively detects minor horizontal stress changes. Studies highlight the “CRR- K_D ” correlation, as load history changes significantly affect “CRR” and “ K_D ” but not “ q_{cn} ”. The “CRR- K_D ” model, combining Eq. (4) and Eq. (5), is recommended [19; 20]:

$$CRR = \exp \left[\left(\frac{q_{cn}}{540} \right) + \left(\frac{q_{cn}}{67} \right)^2 - \left(\frac{q_{cn}}{80} \right)^3 + \left(\frac{q_{cn}}{114} \right)^4 - 3 \right], \quad (4)$$

$$q_{cn} = 25K_D. \quad (5)$$

Eq. (4) is a correlation obtained from Idriss and Boulanger to evaluate the relationship between CRR and q_{cn} . Eq. (5) is a correlation relationship developed by Robertson in 2012 to assess the relationship between q_{cn} and K_D [19, 20]. If both DMT and CPT data are available, it is possible to obtain two independent CRR estimates. One of them uses Eq. (4),

while the other uses a combination of Eq. (4) and Eq. (5). Recent studies have proposed a new approach in which, instead of using two separate correlations to estimate CRR, a single dependence is used that considers both q_{cn} and K_D simultaneously. This method allows obtaining a generalised CRR estimate in the form of a function $f(q_{cn}, K_D)$. An illustration of this approach is provided in Fig.5.

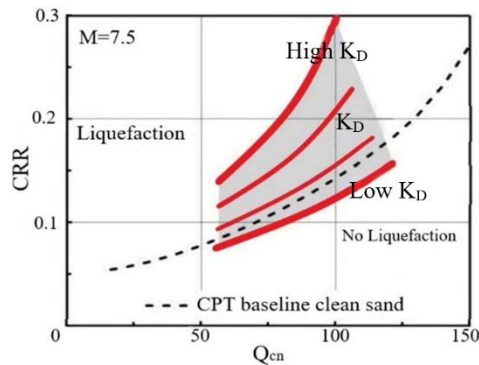


Fig.5 The correlations of the CRR coefficient based on its relationship with q_{cn} and K_D [10]

The results of the study confirm that the methods of creating “P-y” curves based on data obtained from DMT tests provide comparable estimates with the actual behaviour of the soil. The “ $K_D \approx 2$ ” method allows identifying active or long-past sliding surfaces in over-compacted clays. DMT tests are effectively used to track the results of soil compaction, and the compression modulus of deformation proves to be a useful parameter for evaluating compaction.

5. DISCUSSION

Rabarijoely's study examines strength and deformation parameters for foundation design using DMT test data, but its uncertainty analysis methods need verification [15]. The testing methodology significantly impacts result reliability, complicating in-situ data interpretation. The study also explores Marchetti dilatometers for settlement assessment, soil reclamation control, and cyclic liquefaction resistance correlations. Mayanquer investigated correlations between Marchetti dilatometer parameters and geomechanical properties of organic soft soils, identifying relationships with undrained shear strength, elasticity modulus, and density [22]. Developed equations apply to El Garrochal (Quito) but require validation in other regions, as terrain and environmental conditions may affect accuracy.

The study by Amoroso et al. describes the development of a new type of SDMT, which combines the capabilities of traditional DMT with measurements of longitudinal and transverse wave velocities [17]. This new instrument is a combination of a mechanical DMT and four sensors designed to

measure the velocity of volumetric waves [23, 24]. The study covers the procedure for conducting tests using the new SDMT and analyses the results of its application at the test site in Italy. An improved assessment of soil porosity and a more accurate characterisation of the liquefaction process are also being considered. Combining the capabilities of a traditional flat dilatometer with measurements of the velocities of longitudinal and transverse waves seems promising for a more complete assessment of the geotechnical characteristics of the soil [25-27]. Special attention to groundwater conditions allows applying the new method more accurately in various conditions [28]. Although the study presents interesting possibilities, it is important to conduct additional research and verification to confirm the effectiveness and reliability of the new tool in various operating conditions. The differences between the study by the researchers and this paper can highlight the fact that this paper considers the use of a seismic dilatometer, while the above study describes the use of traditional DMT and its combination with other methods.

The study by Bernardi et al. is aimed at evaluating the use of DMT on compacted residual soil and analysing the effect of suction on the obtained parameters [29]. The study showed that DMT successfully detected a trend of changing geotechnical parameters depending on changes in soil absorption profiles. This study also highlights the accuracy and applicability of the DMT method for evaluating soil characteristics, such as the velocity of transverse waves V_s and the compression modulus of deformation M , in various engineering tasks. Both studies are important for understanding the possibilities and limitations of the DMT method in analysing geotechnical soil parameters in various conditions and scenarios. Such a comparison helps to better assess the applicability and effectiveness of this method and to identify the influence of various factors, such as absorption, on the results obtained.

The study by Oberhollenser focuses on using DMT to determine site characteristics and soil parameters [30]. The researcher describes the use of advanced Medusa DMT equipment. The researcher concludes that it is necessary to adjust the pressure readings considering the effects of partial drainage based on an extended test procedure taking into account repeated readings of A (DMT-RA). The researcher correctly draws attention to the importance of considering changes in pore pressure of water during DMT tests and suggests a method for correcting readings, which can improve the reliability of the results obtained. All studies pay attention to the importance of DMT data for the design of engineering structures and understanding the behaviour of soil masses. In addition, efforts are aimed at developing new testing techniques, analysing the results and improving the practical

applicability of the data obtained. The main focus is on the correlation between DMT parameters and other geotechnical characteristics of soils, which allows for a more accurate and reliable assessment of their properties and behaviour in various conditions. Thus, researchers are actively working to improve the DMT testing methodology and expand its application in practical engineering.

6. CONCLUSIONS

DMT and SDMT are methods of field soil testing that are characterised by ease of use and reproducibility of results independent of the operator. DMT is mainly used for settlement forecasting, and other potential use cases. Field measurements in Almaty's Medeu district demonstrated that the average propagation velocities of transverse waves reached 243.96 m/s at 10m depth and 276 m/s at 30m depth, classifying the site as Type 2 soil conditions with calculated seismic accelerations of 0.54g horizontal and 0.48g vertical. The study confirmed high reliability of correlations between mechanical DMT and seismic measurements, though with an approximate 20% relative error between measured and calculated V_s values. The ratio G_0/M_{DMT} showed significant variation (0.5 to 25), predominantly influenced by KD, highlighting the critical importance of KD in accurate V_s predictions.

The research demonstrated that M_{DMT} increases at twice the rate of q_c during compaction, making it a more sensitive indicator of ground improvement. This method effectively monitors horizontal stress changes and evaluates compaction. A combined approach using DMT and CPT data validated cyclic liquefaction resistance assessment, enabling independent result verification. Testing covered undrained shear strengths from 2 to 1,000 kPa and compression modulus measurements from 0.4 to 400 MPa, achieving high productivity (up to 80 meters per day).

The Marchetti dilatometer enables precise soil studies, including dispersed soils and soft rocks, even in very soft or over-compacted conditions. DMT applications include foundation settlement prediction, compaction quality control for road infrastructure, and cyclic liquefaction resistance assessment. It effectively monitors and controls soil compaction, providing data to evaluate technical measures for soil improvement. Additionally, DMT data help establish correlations between soil parameters, including cyclic liquefaction resistance and compression modulus.

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