SDMT – a Tool for in Situ Identification of Collapsible Soils

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ABSTRACT: Loess is a wind blown sediment characterized by an open structure. When moistured or excessively loaded loess structure may collapse causing major problems for engineering structures. Identification of vertical and horizontal distribution of collapse prone zones in this type of soil is a first task of geotechnical investigations. The paper presents two possible ways of identifying collapse prone zones based on SDMT results. Reliability of constrained modulus determined from DMT is also addressed.

1 INTRODUCTION

Loess is general term used to describe widespread yellowish-grey sediment formed by aeolian deposition of predominantly silt fraction. One of the most significant characteristics of loess is its open-loose structure. When moistured or excessively loaded open structure can fail causing sudden volume changes thus endangering engineering structures.

There are different criteria used to identify collapsible soils. Most of these criteria are based on the measurement of dry unit weights (γ_d) or consistency limits or their combination (for an overview see Lutenegger & Saber 1988, Rogers et al. 1994). This imply usual soil mechanics laboratory testing on "undisturbed" soil samples particularly difficult to obtain in loess as emphasized by Milovic (1988), Handy (1995), Rinaldi & Santamarina (2008), Berisavljevic et. al. (2014). One frequently quoted criteria for distinguishing between collapsible and non-collapsible soil is shown on Fig. 1. Results discussed later in the text are included on Fig. 1 as well.

Another issue is related to quantification of volume change that occurs when a soil undergoes collapse. Common is to perform single or double oedometer tests on a high quality soil samples retrieved from test pits in order to estimate settlement that may occur in a soil layer at a particular site (e.g. NAVFAC, 1986). In that way collapse potential (CP) can be determined according to Eq. (1).

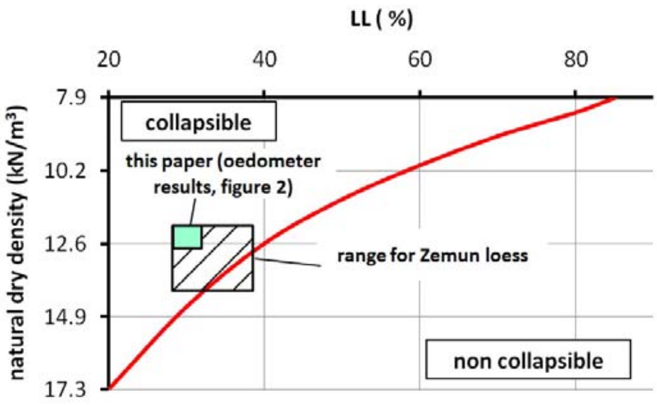

Fig. 1. Criterion for identification of collapsible soils (NAVFAC 1986)

$$CP = \frac{\Delta e}{1 + e_0} \qquad (1)$$

where, Δe = the change in void ratio resulting from wetting; e_0 = natural void ratio. The definition of terms used in Eq. (1) is given on Fig. 2.

Based on authors experience oedometer test results obtained on samples taken from test pits can be used to predict settlements which are comparable with field observations and measurements. Beside laboratory testing field investigations such as plate load test can be used to determine collapse potential under varied moisture environments. These tests are time consuming and require significant effort to perform. Other site investigation tools such as cone penetration test (CPT) and flat dilatometer test (DMT) in combination with shear wave velocity (Vs) measurements are promising alternative for loess characterisation since these tests provide several parameters in one profile. In this paper SDMT results obtained at two sites in Serbian loess are presented.

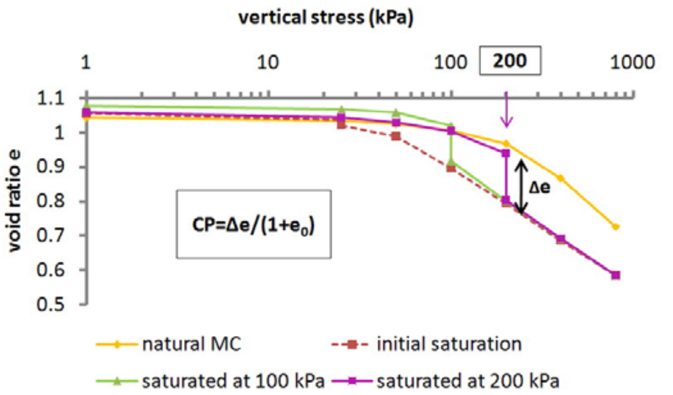

Fig 2. Oedometer test results for „Zemun loess"-first loess horizon

2 REVIEW OF DMT RESULTS IN LOESS

Several papers can be found in literature which focuses on DMT results obtained in loess. They are generally based on the capability of DMT to indicate potential collapse zones and the overconsolidation ratio (Lutenegger & Donchev 1983, Hamamdshiev & Lutenegger 1985, Handy & Ferguson 1994, Handy 1995, Devincenzi & Canicio 2001, and Berisavljevic et. al. 2014).

Particularly interesting results were obtained by Lutenegger & Donchev (1983). They were first to notice that DMT is able to indicate „low density" – collapsing zones in loess. They reported extremely low K_D values ranging from 0.3 to 0.6 in collapse prone zones and I_D>1.8, i.e. range represented by sand and silty sand. Vertical profiles of I_D and K_D for one of the locations reported by Lutenegger & Donchev (1983) are shown on Fig. 3. Since their result refers to Northern Bulgaria, geographically very close to Serbia, similarity with results presented here can be attributed to this fact.

3 SEIZMIC DILATOMETER

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT) with a seismic module placed above the DMT blade.

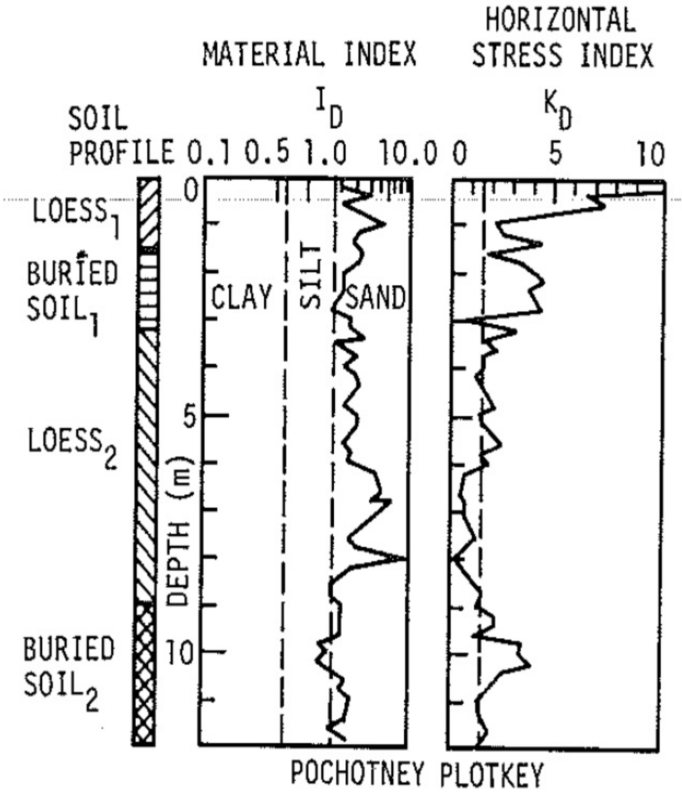

Fig. 3. DMT (I_D, K_D) results reported by Lutenegger & Donchev (1983)

The seismic module is used for obtaining the vertical profile of shear wave velocity Vs. From Vs the maximum shear modulus G_0 may be determined using the theory of elasticity. Measurements of Vs are usually obtained every 0.5 m. Detailed description of the DMT equipment and test procedure can be found in Marchetti (1980) and Marchetti et. al. (2001). The basic parameters obtained from DMT are material index (I_D), horizontal stress index (K_D) and dilatometer modulus (E_D) defined as:

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \quad (2)$$

$$K_D = \frac{p_0 - u_0}{\sigma_v'} \quad (3)$$

$$E_D = 34.7(p_1 - p_0) \quad (4)$$

where, u_0 = preinsertion equilibrium pore pressure, σ_v' = preinsertion vertical effective stress, p_0 = corrected first reading, p_1 = corrected second reading.

Parameters given by Eq. (2) to Eq. (4) are intermediate parameters used for derivation of common geotechnical parameters. For derivation procedure refer to Marchetti et al. (2001).

4 PROPRETIES OF EXAMINED LOESS

4.1 *Zemun loess plateau*

The most relevant engineering properties of Zemun loess are described in Markovic (1987). Generally, three to five loess horizons separated by buried soils can be distinguished. Overall thickness can vary considerably, usually between 15 and 35 m. First two loess horizons lie above water level where degree of saturation is Sr=40-70 %. From the petrographic perspective the most common minerals of the coarse fraction are: quartz 50-55 %, feldspar and muscovite. Also, significant is content of some silica rocks such as cherts and quartzite. Mineralogical examinations showed that fine fraction is composed of predominantly clay minerals (illite and montmorillonite) and calcite. All five horizons have very similar mineralogical composition indicating that material is deflated from the same deflation region. Natural void ratio of loess above water level is e_0~1.0-1.1. Calcium carbonate nodules and microcrystals are found in soil mass varying between 7 % and 20 %. The grain size distribution consists of sand (5-15 %), silt (60-75 %) and clay fraction (15-25 %). Sand fraction increases with depth toward sand layer underlying loess. The liquid limit ranges between LL=30-40 %, the plastic limit PL=20-22 % and the plastic index IP=10-18 %. According to USCS it can be classified as low plasticity clay CL. Clay minerals are major cementing material in the way that they connect coarser silt and sand particles. γ_d ranges between 12.3 and 14.5 kN/m^3. Lower bound of γ_d correspond more closely to block samples taken from test pits while upper bound correspond to samples obtained by conventional drilling. This indicate that effect of mechanical disturbance of samples is more pronounced when sample is retrieved from borehole. According to Markovic (1987) coefficient of lateral earth pressure at rest, determined from K_0-triaxial test, for collapsible Zemun loess ranges between K_0=0.1-0.2 for stresses less than 300 kPa with a tendency to decrease with decreasing moisture content. Based on the γ_d-LL criterion, indicated on Fig. 1, most of the data for Zemun loess fall in collapsible soil region.

At particular location where SDMT/DMT have been performed three loess horizons (L_1 2.0-6.0 m, L_2 7.0-11.5 m and L_3 13.0-16.2 m) are distinguished separated by buried soil (b1 and b2) which contains higher clay content compared to loess. First two meters represent more clayey weathered loess, Fig. 4. Water level measured in piezometers was at 10 m depth from the ground surface.

First loess horizon is highly collapsible which is evident from oedometer test results shown on Fig. 2. Three single oedometer tests were performed, on samples taken from test pit, with stress level prior to saturation: 25 kPa, 100 kPa and 200 kPa. One sample was tested at the natural moisture content. The solid region indicated on Fig. 1 refers to results obtained on samples taken from test pit.

4.2 *Deliblato loess*

Deliblato sands are located in the south-east part of the Panonian plain within 60 km from Belgrade area where the first site is located. Its genesis is still not clear. It is believed that it was formed over the existing loess plateau by aeolian deposition of silica and carbonate sands deflated from accumulated nearby river sediments. Deliblato sands are surrounded by loess plateau where two SDMTs were performed. Edge of loess plateau is recognizable by vertical slopes with heights of approximately 15 m.

The soil profile consist of 12 m thick loess horizon underlain by fine sand to sandy silts interbedded with low plastic clay layers, Fig. 5. First two to three meters of loess horizon are humified and rich with carbonate concretions. Laboratory tests were performed on samples taken from one test pit and two boreholes (adjacent to SDMT). Following results were obtained. Sr=20-30 %, e0~1.0-1.07, calcium carbonate content in soil mass vary between 10-20 %. The grain size distribution consists of sand (5-15 %), silt (70-85 %) and clay fraction (10-15 %). The liquid limit ranges between LL=28-33 %, the plastic limit PL=18-21 % and the plastic index IP= 8-12 %. According to USCS it can be classified as low plasticity clay CL. γd=12.9-13.9 kN/m3. Again lower γd is obtained from test pit.

For this site identification of collapsible soil is accessed through Fig. 1 and value of liquid index (IL). Points representing pairs γd-LL plot at approximately the same distance from the boundary line between collapsible and non-collapsible soil as for Zemun loess. On the other hand, Yuan & Wang (2009) showed that samples with lower IL have higher collapsibility when moistured. Samples obtained from Deliblato loess have value of IL in the range (-1.0)-(-1.4), while for Zemun loess value of IL is significantly higher 0.1-(-0.4). Since oedometer tests have not been performed on samples obtained from Deliblato loess in order to obtain numerical value of collapsibility (current phase of research) it is assumed that Deliblato loess is more collapsible compared to Zemun loess based on the Yuan & Wang (2009) criterion.

5 SDMT PROFILES IN LOESS

5.1 *Intermediate parameters I_D and K_D*

Typical SDMT results obtained for Zemun and Deliblato loess are shown on Fig. 4 and 5, respectively. For Zemun site three DMTs were performed from which two with Vs measurements. From Fig. 4 it is observed that: in the first 6 m (first loess horizon) K_D values are extremely low (K_D<0.6), while I_D values are in the sand (Id>3.3) and subordinately in the silty sand region (1.8<Id<3.3). These results are consistent with results reported by Lutenegger & Donchev (1983) indicating collapsible loess. In the second loess horizon which is believed to be less collapsible compared to the first loess horizon, due to yearly fluctuations and rise of ground water level, K_D is approximately 1.2 above water level decreasing to 0.6 below it. Value of I_D shows less sensitivity to changes in moisture content compared to K_D as seen from Fig. 4. In buried soil K_D increases while I_D decreases compared to loess due to higher clay content and more dense structure.

For Deliblato loess two SDMTs have been performed. Similar trends of K_D and I_D as for Zemun loess are observed as shown on Fig. 5. In the first 12 meters (excluding top layer) values of K_D are extremely low K_D<0.6, while I_D identifies soil as sand (Id>3.3). Slightly higher values of K_D (K_D<0.6-0.9) and lower values of I_D are obtained from SDMT-2 in the first eight meters. This may be attributed to higher silt and lower sand content in the first six to eight meters, which have been determined in the laboratory and observed in the field from adjacent borehole.

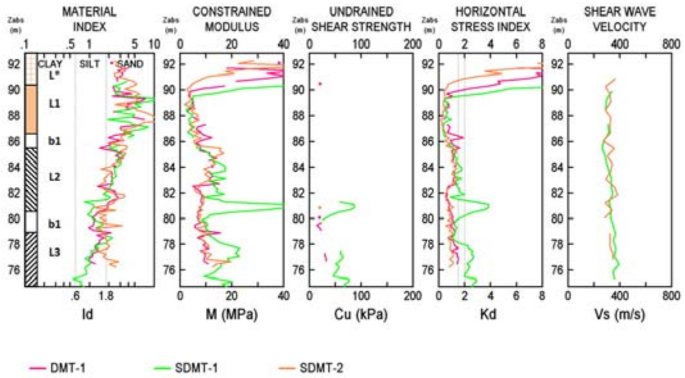

Fig. 4. SDMT/DMT results for Zemun loess

For both sites values of I_D seems to be high in collapsible loess compared to results of sieve analysis and general description of loess as silty soil. This is not unusual since I_D was not evaluated for this soil type. It should be mentioned that I_D is a parameter reflecting mechanical behavior, rather than results of sieve analysis (Marchetti 2001).

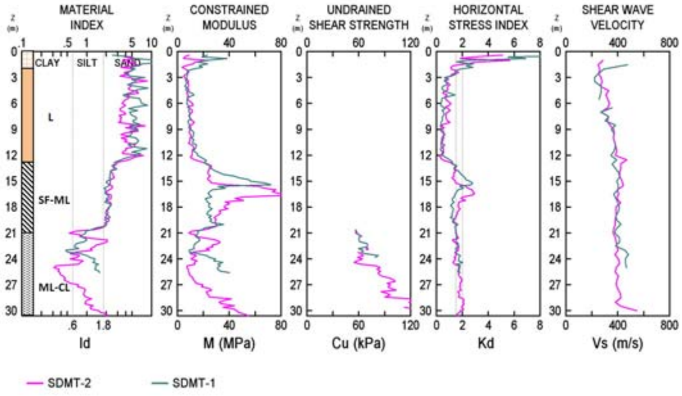

Fig. 5. SDMT results for Deliblato Loess

5.2 *Shear wave velocity - Vs*

Combining Vs measurements with results obtained by mechanical DMT gives significant advantage in soil characterization. Influence of cementation on small strain stiffness (also Vs) is emphasized by many authors (e.g. Eslaamizaad and Robertson 1996, Fernandez and Santamarina 2001, Schnaid 2005, Yun and Santamarina 2005, Rinaldi and Santamarina 2008). Based on theoretical considerations and experimental data Fernandez and Santamarina (2001) and Yun and Santamarina (2005) have shown that the behavior of natural soils is greatly affected by cement content and confining pressure. They also identify two stress-regions: a low-stress region where behavior is controlled by the cementation, and a high-stress region where the response is controlled by the state of stress. This is of particular importance for loess where the confining pressures are low and a cement controlled region prevails. Sawangsuriya et. al. (2008) showed that for compacted soils at relatively low confining pressures, decrease in moisture (increase in suction) would cause increase in G_0 (Vs). This trend is assumed to apply for loess as well.

From previous discussion and Figs. 4-5 it is obvious that in loess high Vs coexist with low values of K_D. This phenomenon can be explained by different shear strain magnitudes induced during blade penetration and shear wave propagation in soil. Sensitive loess structure is able to resist small shear strains induced by shear wave while it collapses during blade penetration. It is assumed that K_D value reflect different material disturbed by blade penetration. Berisavljevic et. al. (2014) found that G_0/M_{DMT} ratio tend to be high for loess (G_0/M_{DMT}>10). For Zemun loess first collapsible horizon is characterized by the ratio G_0/M_{DMT}>21, for K_D<0.6. This ratio for Deliblato loess is lower between 10-20 for K_D<0.6 (0.9) due to higher M_{DMT}. Thus, it is interesting to explore why M_{DMT} is lower for Zemun loess (first collapsible horizon) compared to Deliblato loess. Laboratory test results indicated that Zemun loess is more clayey (higher plasticity), with higher Sr which could also be an indication of lower collapsibility compared to Deliblato loess. Generally, M_{DMT} decrease with increase in plasticity while higher moisture means lower suction contribution to strength of loess. These factors could yield lower M_{DMT} for Zemun compared to Deliblato loess. It is also expected that the same factors would have influence on G_0. Since this is not the case it is believed that different level of disturbance caused by blade penetration is the main cause of different values of M_{DMT} for two sites. At the present phase of research it seems that more collapsible loess tend to have lower G_0/M_{DMT} ratio for K_D<0.6 (0.9). This findings are opposite from general trend that ratio G_0/M_{DMT} decreases as K_D increases (see Marchetti et.al. 2008).

Unit weights of the first loess horizon estimated from DMT, according to the chart given in Marchetti et al. (2001), are about 15% higher than the values determined from block samples. It is suggested to reduce G_0 for 15% to reduce possible mistakes. Future research will involve quantification of collapse for Deliblato loess using the same laboratory equipment and test procedure as for Zemun site.

5.3 *Constrained modulus*

A review of available experience between DMT-predicted and observed settlement have been made by Monaco et.al. (2006). One of their conclusions are that the constrained modulus M_{DMT} can be considered a reasonable "operative modulus", i.e. introduced into the traditional elasticity theory formulae predicts settlements with reasonably good accuracy for foundations in "working conditions" (say for a safety factor Fs ≈ 2.5 to 3.5). Derivation of M_{DMT} can be found in Marchetti (1980) and Marchetti et.al. (2001).

Here M_{DMT} is considered as operative modulus for the stress level less than about 150-200 kPa. This stress level („site specific") is important because if exceeded significant reduction in stiffness could be expected. This is observed on Fig. 2 for sample tested at natural MC where deformation starts to develop more rapidly after 150-200 kPa. This stress level can be treated as apparent preconsolidation stress for natural MC (see e.g. Alonso et.al. 1990).

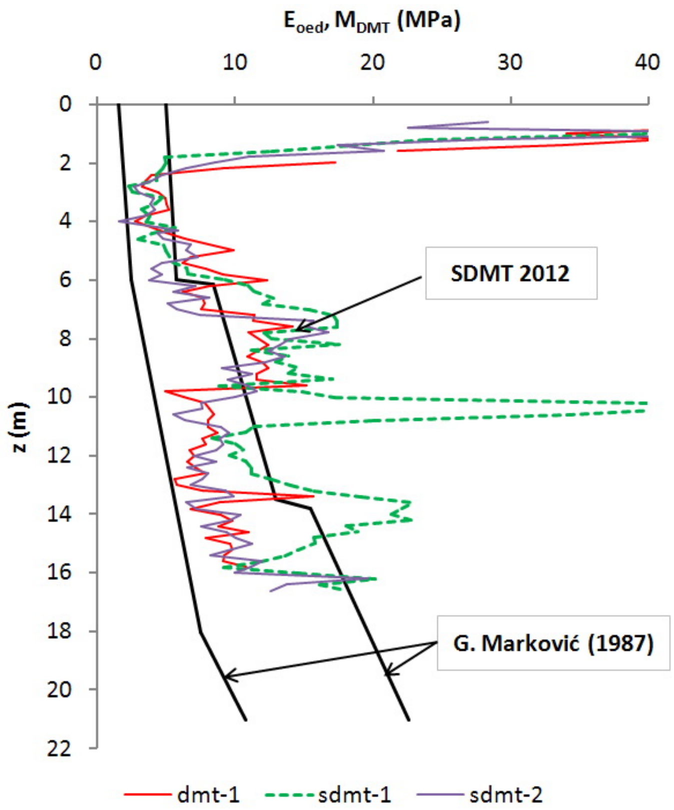

Fig. 6. Comparison of E_{oed} and M_{DMT} for Zemun loess

Fig. 6 show distribution of oedometer modulus (E_{oed}) versus depth for Zemun loess. For the zone above water (~10 m) E_{oed} is determined for vertical stress below 150 kPa. The data were taken from Markovic (1987) and were evaluated from more than 500 samples. Upper and lower bound correspond to different natural moisture and density conditions (probably different level of mechanical disturbance). Fig. 6 includes profiles of M_{DMT} obtained for Zemun loess from DMT-1, SDMT-1 and SDMT-2. It can be seen that M_{DMT} compares very well with E_{oed}, particularly good agreement is observed in the first 6 m (collapsible loess). It should be mentioned that SDMT-1 profile from tenth meter below differs from other two tests. This difference is also confirmed by drilling where silty sand layer was encountered at these depths.

Usually, settlement prediction of foundations on collapsible soil is performed according to recommendations given by Jennings and Knight, (1975) using the results of a double or single oedometer test results. Also, experience has shown good agreement between calculated, according to one-dimensional formula based on E_{oed} values given on Fig. 6, and observed settlements for objects constructed in Zemun area. Thus, it is argued that M_{DMT} values are sufficiently accurate to be used for settlement prediction of shallow foundations constructed on collapsible Zemun loess at natural moisture content.

5.4 *Additional observations*

During testing following observations were made:

- in collapsible loess (both site) when performing C-reading the membrane did not return to its seating position (buzzer was off). This is common for sands above water level.
- false energizations due to vibrations of the penetrometer were detected at depths of up to 8 m at Zemun site. For this reason, the penetrometer had to be shut down while performing seismic tests.
- total thrust force needed to advance blade+seismic probe through loess is less than approx. 1000 kg. It is argued that test can be performed with a drill rig which can be useful on smaller projects. Although, small adjustment is required to connect seismic probe to drill rig.

6 LOESS IN RELATION TO OTHER SOIL TYPES

Pairs of points of K_D, G_0/M_{DMT} and I_D obtained in loess are shown on Fig. 7 as three dimensional surface diagram. Also, three other „normal" soil types are included on the same diagram in order to observe the difference between them and the collapsible loess. The purpose of Fig. 7 is to indicate that data for collapsible loess are „isolated" in K_D-G_0/M_{DMT}-I_D space from „normal" soil types frequently encountered during site investigations. On the vertical axis lines representing boundaries of different G_0/M_{DMT} ratios for clays, silts and sand are included. These boundaries have been reported by Marchetti et.al (2008).

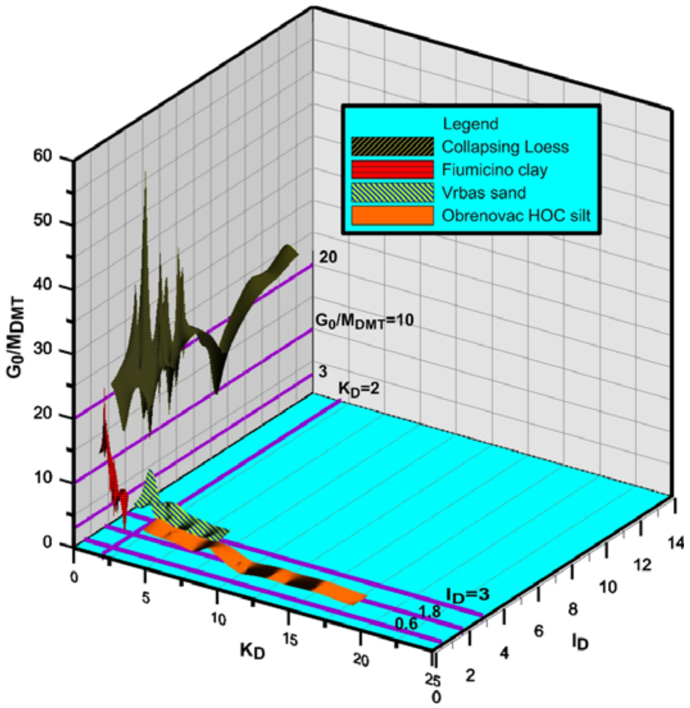

Fig. 7. 3D surface diagram showing relation of collapsible loess to „normal" soil types

7 CONCLUDING REMARKS

The results presented in this paper have indicated the following:

- DMT can be efficiently used to isolate collapsible from non-collapsible loess based on intermediate parameters.
- Collapsible zones are recognized by extremely low K_D<0.6 and high I_D>3 values.
- Vs measurements (SDMT) provide valuable information regarding loess structure. In collapsible loess Vs is generally higher than 260 m/s.
- G_0/M_{DMT} ratio is site specific, i.e for Zemun loess collapsible zones are recognized by G_0/M_{DMT}>21 while for Deliblato loess collapsible zones are recognized by G_0/M_{DMT}>10. The difference in G_0/M_{DMT} ratio for two sites is caused mainly by different M_{DMT} values.
- G_0/M_{DMT} ratio in loess have tendency to decrease with decrease in liquid index. Lower IL may be an indicator of higher collapsibility thus it is argued that collapsing loess with lower G_0/M_{DMT} ratio for the same range of K_D have higher collapsibility when moistured.
- M_{DMT} is sufficiently accurate to be used for settlement prediction of shallow foundations constructed on collapsible Zemun loess at natural moisture content (for stress levels less than 150-200 kPa).
- G_0 obtained from SDMT in collapsible loess should be reduced by 15 % since it is derived from unit weights which are 15 % higher than unit weights obtained in laboratory.

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