Shear strength of municipal waste materials from two landfills in Serbia

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ABSTRACT: In this paper the results obtained by laboratory testing of municipal waste materials from two different sanitary landfills in Serbia are presented. For defining parameters of shear strength, linear shear strength equation was used, which is determined from mobilized shear stresses at horizontal displacement of $\Delta l = 14$ mm - for each of normal stresses ($\sigma'_n = 25$, 50 and 100 kPa). Also, an interpretation of the test results was made for nonlinear shear strength envelope with logarithmic and hyperbolic functions. Thus obtained results are compared with the proposed linear Coulomb-Mohr-Terzaghi strength equations and nonlinear forms of the logarithmic equation proposed by Zekkos (2005). It was concluded that the proposed nonlinear shear strength envelope with hyperbolic shape, compared to the envelope of logarithmic form, is in better agreement with the linear Coulomb-Mohr-Terzaghi envelope.

1 INTRODUCTION

Shear strength or the shear stress parameters for municipal solid waste have been obtained in different ways that are divided into three groups: laboratory tests on small or large samples using standard or special-design equipment, in situ tests and assessments of the shear strength parameters based on back analyses of the landfill slope stability. Published approaches to the interpretations of test results still differ, based on various assumptions. Shear strength of municipal solid waste has been much studied and the reported results are mainly those of laboratory tests on samples of different sizes: Landva & Clark (1986), Gabr & Valero (1995), Manassero et al. (1996), Eid et al. (2000), Pelkey et al. (2001), Dixon & Jones (2005), Langer (2005), Zekkos (2005), Zekkos et al. (2007), Kavazanjian (2006), Athanasopoulos et al. (2008), Bray et al. (2009), Stark et al. (2009), and many others.

Some authors are of the opinion that the waste shear strength also considers the tensile strength activated by shearing. Kölsch (1996) and later Athanasopoulos et al. (2008) tried to explain shear strength of solid waste including reinforcing elements.

Direct shear tests on undisturbed samples in situ certainly give more realistic values than the measured shear strengths of the municipal artificially prepared samples. Tests in situ by Houston et al. (1995), Withiam et al. (1995), Mazzucato et al. (1999), Thomas et al. (1999), Caicedo et al. (2002) made worthy contributions to the description of the municipal waste shear strength.

2 LABORATORY TESTS SAMPLES PREPARATION

Municipal waste tested in laboratory for the shear strength was sampled by drilling or excavating from two landfills in Serbia (active landfill in Novi Sad and old Ada Huja landfill in Belgrade – closed 40 years ago). The composition of waste (Tab. 1) is based on the materials sorted and classified following instructions of the S.W.A.-Tool (European Commission, 2004).

Table 1. Composition of analyzed municipal waste

kind and denotation of waste by S.W.A. - Tool catalog	mass (%)	
	Ada Huja landfill, Belgrade	landfill for Novi Sad
Wood – W2	1.0	2.9
Paper and Cardboard–PC3	3.7	4.2
Plastics – PL4	5.6	6.4
Glass – G5	4.9	6.3
Textiles – T6	2.3	1.8
Metals – M7	1.9	2.4
Complex Products – C9	1.1	1.3
Soil – IN10 01	34.1	29.4
Ceramics – IN10 02	6.1	5.3
Unclassified (fines) – F12	39.3	40.0

Table 1 shows the old waste predominantly composed of unsorted and soil materials characteristic of Serbian municipal landfills older than thirty years (Rakić et al. 2011a).

Preparation of waste samples consisted of reducing the particle size (d) to suit the shear box (L) i.e. L/d ≥ 5. Depending on the apparatus used, the maximum particle size (d) was 12-20 mm. A small proportion only (not higher than 5%), mainly of plastics, textiles and paper particles, were somewhat coarser (max. 40 mm).

Samples were artificial, prepared and separated into four series (A, B, C, D), each series of three specimens (36 test samples) different in unit weight and natural moisture (Tab. 2).

Table 2. Basic identification and classification data for test samples

series	sample labels	w (%)	γ (kN/m^3)	G_s	e
	U-1	37.2	10.6		1.848
A	U-2	36.4	15.0	2.2	1.000
	U-3	27.2	17.5		0.599
	U-4	39.8	11.1		1.519
B	U-5	35.0	12.1	2.0	1.231
	U-6	36.9	13.4		1.043
	U-7	30.9	10.0		1.683
C	U-8	33.9	12.1	2.05	1.268
	U-9	32.9	14.3		0.905
	U-10	28.7	10.0		1.638
D	U-11	29.7	11.6	2.05	1.292
	U-12	31.8	14.0		0.930

Waste samples were prepared from the Belgrade (Series A) and Novi Sad (Series B) and the mixture from the two landfills (Series C and D). Samples from Series A, B and C were compressed in horizontal layers, similarly to the waste deposition on the landfills. Samples of Series D had reinforcing particles oriented at an angle $\alpha = 90^0$ to the horizontal plane of shearing in the shear box.

3 DIRECT SHEAR TEST RESULTS

Shear strength of the waste was determined from the direct shear tests in boxes 60 mm x 60 mm and 100 mm x 100 mm. For consolidation of samples, normal stresses (σ'_n) were selected of 25, 50 and 100 kPa. In most test samples, subjected to shearing parallel with the reinforcing particles (Series A, B and C), the relation shearing stress-displacement indicated different behaviour of waste in relation to compaction or to unit weight.

For less compacted samples with unit weight $\gamma \leq$ 12.1 kN/m^3, the stress-displacement relation was closest to the behaviour of soil with strain hardening, so that the strains were inadequate to mobilize the peak shearing resistance of the waste (Fig. 1).

The stress-displacement relation of the dense samples with $\gamma \geq 13.4$ kN/m^3 indicated waste behaviour similar to the waste with plastic failure (Fig. 2).

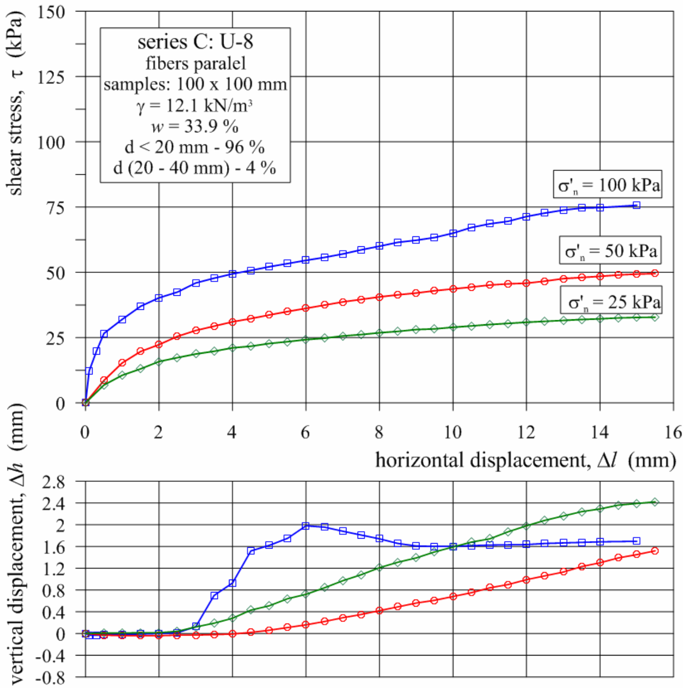

Figure 1. Characteristic relation of the shearing stress and displacement for loose compacted samples ($\gamma \leq 12.1$ kN/m^3).

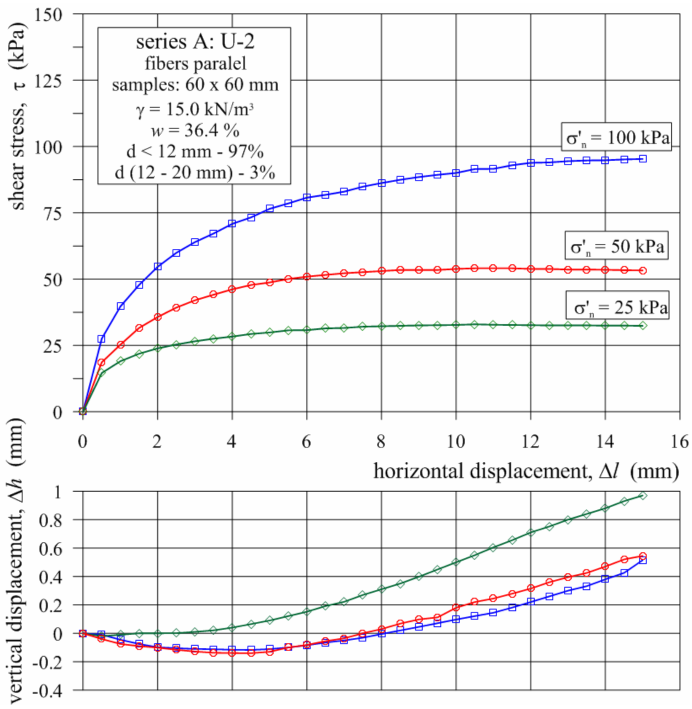

Figure 2. Characteristic relation of stress and displacement during shearing for dense samples ($\gamma \geq 13.4$ kN/m^3).

The shearing stress-displacement relation for samples including reinforcing particles oriented normal to the shear plane (Series D) had a different behaviour, because all samples behaved similarly to the soil with strain hardening. The similarity of the relation indicated that different densities didn't have great effect on the shape of the stress-strain behaviour for these samples. The test results, for a characteristic sample from series D, are represented in Figure 3.

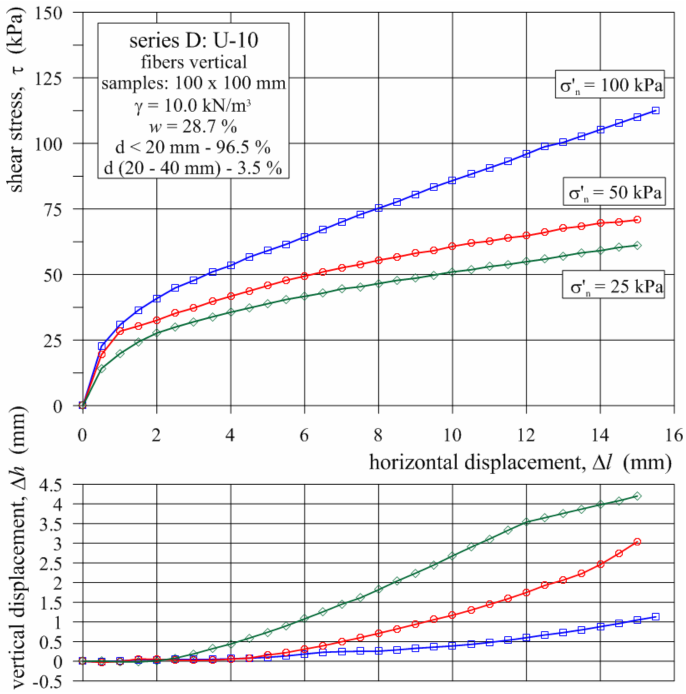

Figure 3. Characteristic relation of the shearing stress and displacement for samples with the particles oriented normal to the shearing plane.

Vertical deformations of samples also were measured during the shearing. It was noted that the upper frame of the box-shear apparatus had heaving with most samples. The heaving was greatest with the samples consolidated at the lowest normal stress σ'_n = 25 kPa (Fig. 4).

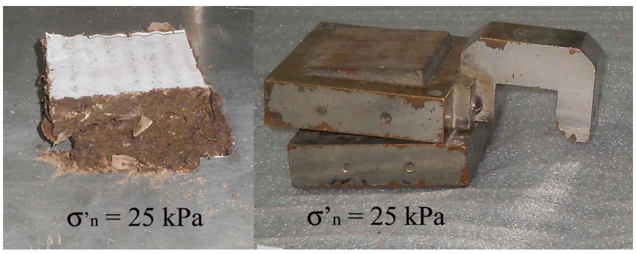

Figure 4. Characteristic heaving of the box-shear apparatus upper frame and a view of the sample after shearing.

After the test completion and the sample extraction, the shear surface remained horizontal, with only the upper frame front heave.

4 SHEAR STRENGTH DETERMINING

4.1 *Linear shape of the shear strength equation*

For the shear strength of municipal solid waste the authors of reference literature mainly recommend the linear Coulomb-Mohr-Terzaghi equation, using mobilized angle of internal friction (φ'_{mob}) and mobilized cohesion (c'_{mob}). In the case of unexpressed failure (which is a common case), the horizontal displacement (Δl), which depends on the size of the test sample, is taken to vary between 7 mm and 150 mm. With this criterion applied, the mobilized shear strength for displacement (Δl) of 14 mm was used in the interpretation of the test results. This failure criterion is not perfectly adequate for each normal stress level in view of the fact that for some samples, at a normal stress σ'_n = 25 kPa, the peak shearing resistance was clearly expressed. Where this was the case, the shear strength parameters were combined from the mobilized and peak resistances. The interpretation was based on the linear shape of the Coulomb-Mohr-Terzaghi equation for shear strength and on the nonlinear failure envelope, using relations for the logarithmic and the hyperbolic shapes.

In view of different unit weights of the prepared samples, shear strengths were determined for loose ($\gamma \leq 12.1$ kN/m^3) and for dense ($\gamma \geq 13.4$ kN/m^3) waste (Fig. 5).

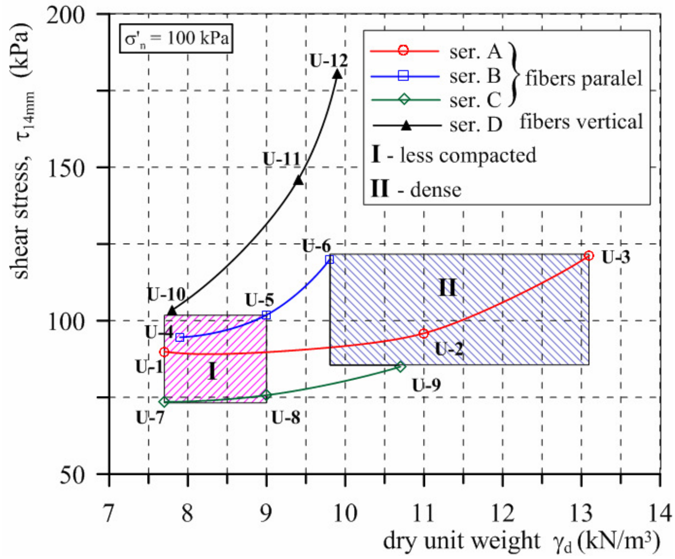

Figure 5. Unit weight versus shearing resistance for municipal waste.

Minimum and maximum shear strengths were determined for both conditions and their average values taken to be characteristic of the dense and the loose landfills in Serbia.

Samples from Series D were not considered, because of their different particle orientation. They had much higher angle of internal friction (φ'_{mob}) and cohesion (c'_{mob}) than samples of the other three series, which varied in relation to the unit weight within the ranges from $\varphi'_{mob} = 32^0$ - 51^0 and from c'_{mob} = 31 - 57 kN/m^2, respectively.

It was concluded for both considered conditions that maximum shear strength was preferential in samples of the Series B (municipal waste from Novi

Sad landfill), which supports the general assumption that shearing strength decreases with the degradation of the waste.

Average values of the shear strength parameters for the Coloumb-Mohr-Terzaghi equation are plotted in Figure 6 and Figure 7 (Rakić et al. 2011b).

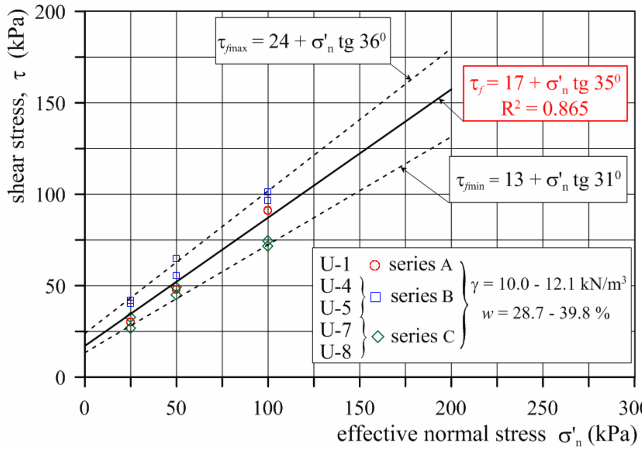

Figure 6. Relation of shearing stress and displacement for loose compacted samples.

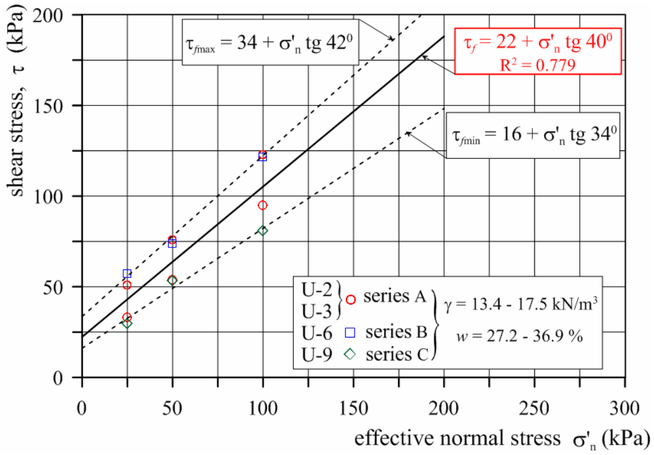

Figure 7. Relation of shearing stress and displacement for dense samples.

Straight lines of the failure envelopes were compared with those recommended by other authors and extensively used. Shear strength of the loose waste (best fit to the published data) seems to be between the upper and lower limits, which confirm a comparatively good agreement with the published values. As the shear strength parameters were obtained for dense waste, the range of their values, recommended by Sanchez-Alciturri et al. (1993) and by Gabr & Valero (1995), could be widened and the lower limit proposed (Fig. 8).

Figure 9 shows the linear strength envelope for loose compacted and well compacted municipal waste, which are compared with the proposals of other authors, which are widely used in practice.

Shearing strength parameters are computed for all the measured horizontal displacements (Fig. 10).

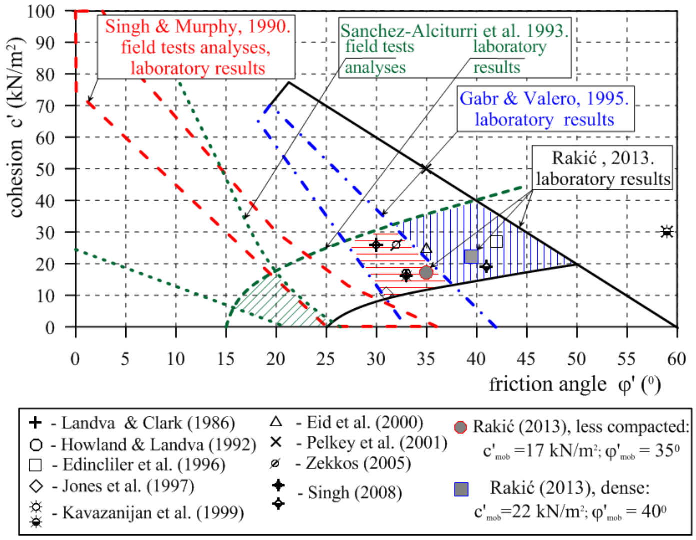

Figure 8. Comparative illustration of the shear strength parameters from reference sources.

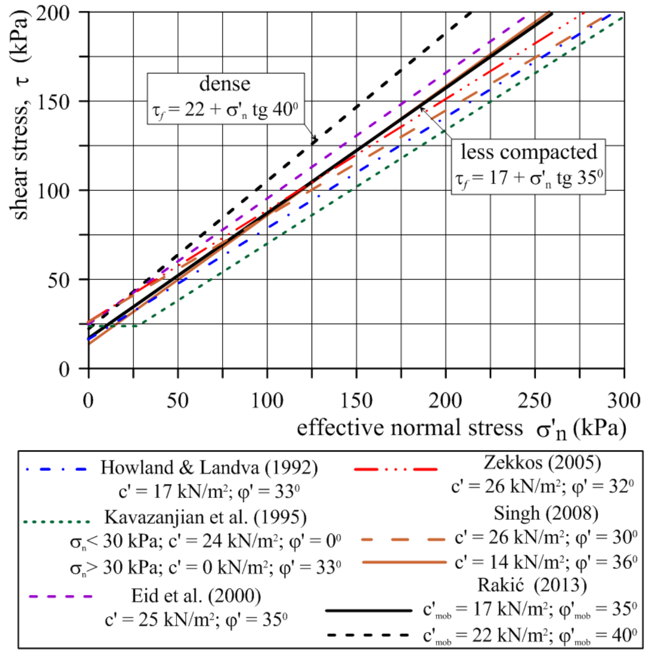

Figure 9. The recommended and the reference straight-line failure envelopes.

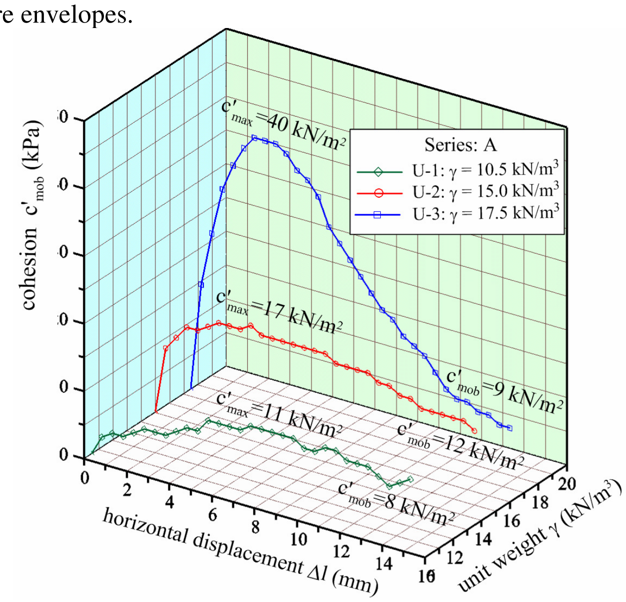

Figure 10. Mobilised cohesion in relation to shearing displacement and unit weight - Series A samples.

In most of tested samples, which had particle orientation parallel to the shear plane, cohesion reached maximum value in the zone of comparatively small horizontal displacements (Δl = 2-5 mm) and depended on the sample compacted. For greater displacements (Δl > 12 mm), it was found that compression didn't have great effect on the cohesion, as the increments for all tested samples were within the range $\Delta c'_{mob}$ = 2-5 kN/m^2. Orientation of the reinforcing particles, however, had a notable effect on cohesion, as the Series D examples, which had reinforcing particles normal to the shearing plane, demonstrated maximum cohesion values of Δl = 13-15 mm (Fig. 11) in the zone of large horizontal displacements (Rakić, 2013, unpubl.).

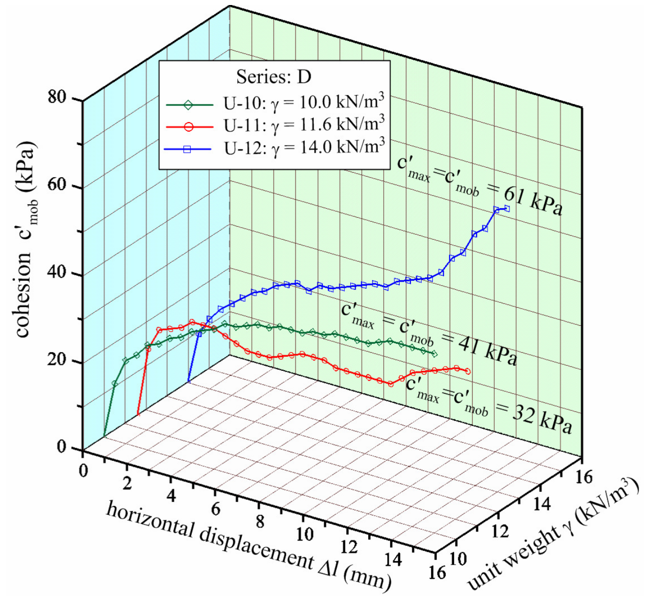

Figure 11. Mobilised cohesion in relation to the shearing displacement and unit weight - Series D samples.

Unlike cohesion, the angle of internal friction grows with the horizontal displacement (Fig. 12).

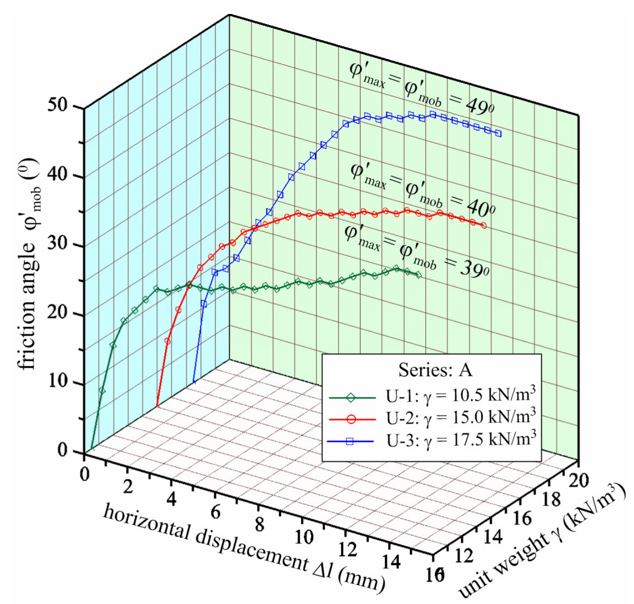

Figure 12. Mobilised angle of internal friction in relation to the shearing displacement and unit weight - Series A samples.

Jessberger & Kockel (1993) and Gabr & Valera (1995) came to similar conclusions that mobilized angle of internal friction in the old degraded waste increased to a maximum at certain displacement and remained constant at subsequent displacements. Unlike cohesion, however, unit weight can not markedly change the angle of internal friction within a small range of displacements (Δl=3-4 mm), because at Δl=3 mm the value of the mobilized angle of internal friction varies only within $\Delta\varphi'_{mob}=2^0$.

Like with cohesion, the orientation of reinforcing particles has a marked influence on the mobilized angle of internal friction values and the angle increases with the horizontal displacement (Fig. 13).

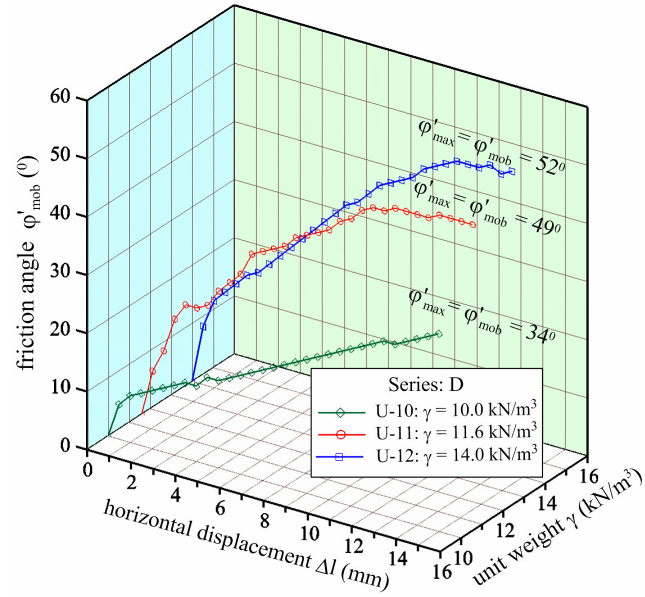

Figure 13. Mobilised angle of internal friction in relation to the shearing displacement and unit weight - Series D samples.

4.2 *Nonlinear shape of the shear strength equation*

On the basis of the published and own research data, Zekkos (2005) states that linear failure envelope may be a good fit of the obtained data, but notes that a nonlinear envelope is more accurate and recommends the use of the nonlinear envelope of logarithmic shape.

An equation of shear strength in the logarithmic shape was first published by Nobari & Duncan (1972) to determine shearing resistance of a rockfill. Zekkos (2005) recommended its use for shear strength of the municipal solid waste. Based on direct shear test results for sixteen solid waste samples (γ = 10.2 - 15.1 kN/m^3) and on the results of other researchers, he recommended the following logarithmic shear strength equation:

$$\tau_f = 15.0 + \sigma'_n \cdot \tan\left[36.0 - 5.0 \cdot \log\left(\frac{\sigma'_n}{p'_a}\right)\right] \qquad (1)$$

The same author compared the recommended logarithmic nonlinear failure envelope with the previous linear envelopes by Kavazanjian et al. (1995), Manassero et al. (1999), Eid et al. (2000) and found them fundamentally similar, noting that an advantage of the nonlinear failure envelope was its being based on a larger number of the direct shear tests performed on wastes from all over the world.

Nonlinear shear strength equation, both logarithmic and hyperboles shapes also were used in the interpretation of the test results. Samples from the group of loose compacted waste ($\gamma \leq 12.1$ kN/m^2) were tested for mobilized cohesion c'_{mob} = 0, 5 and 10 kPa. The linear envelope obtained by the mobilized cohesion c'_{mob} = 10 kPa that best fitted the nonlinear shear strength equation is:

$$\tau_f = 10.0 + \sigma'_n \cdot \tan\left[37.0 - 11.0 \cdot \log\left(\frac{\sigma'_n}{p'_a}\right)\right] \tag{2}$$

A nonlinear envelope was similarly developed for dense waste:

$$\tau_f = 10.0 + \sigma'_n \cdot \tan\left[43.0 - 12.0 \cdot \log\left(\frac{\sigma'_n}{p'_a}\right)\right] \tag{3}$$

The results for both groups of samples are represented in Figure 14 and Figure 15.

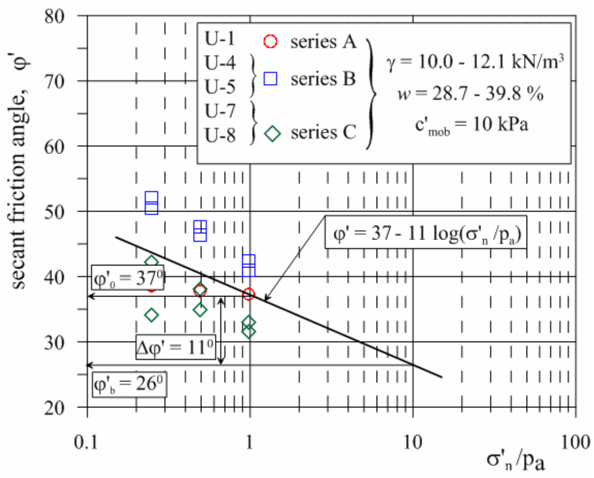

Figure 14. Nonlinear shear strength equation of logarithmic shape for loose compacted waste.

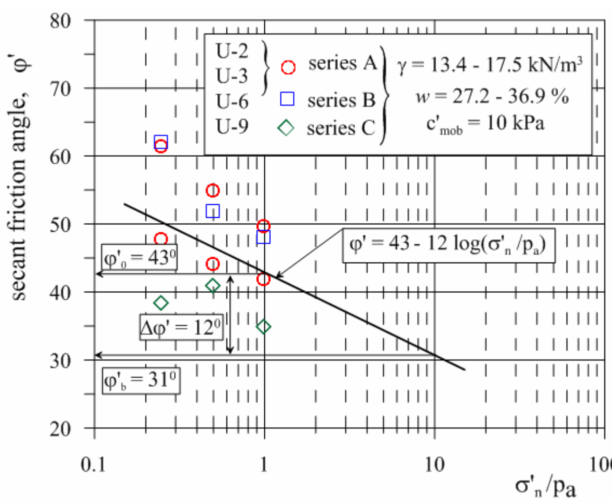

Figure 15. Nonlinear shear strength equation of logarithmic shape for dense waste.

The nonlinear failure envelope may be determined using hyperbolic shape relation proposed by Maksimović (1989), Maksimović (1993), who considers that a change in the effective secant angle of the shearing strength may be expressed in relation to the normal shearing stress written as:

$$\varphi' = \varphi'_B + \frac{\Delta\varphi'}{1 + \sigma'_n / p_N} \tag{4}$$

Figures 16-17 are geometric representations of the parameters in the above equation.

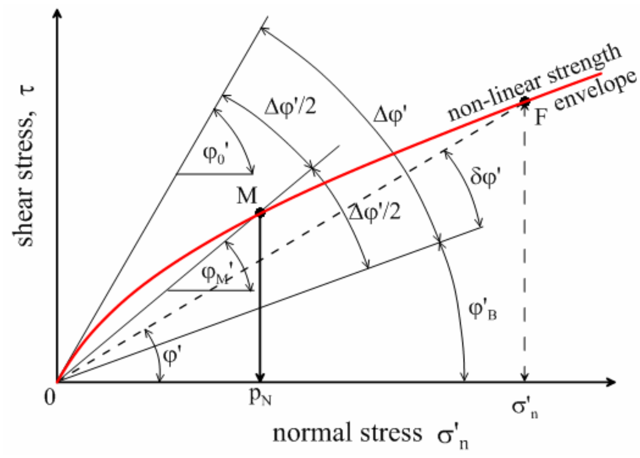

Figure 16. Geometric representation of the hyperbolic shape of a nonlinear envelope (Maksimović, 1989).

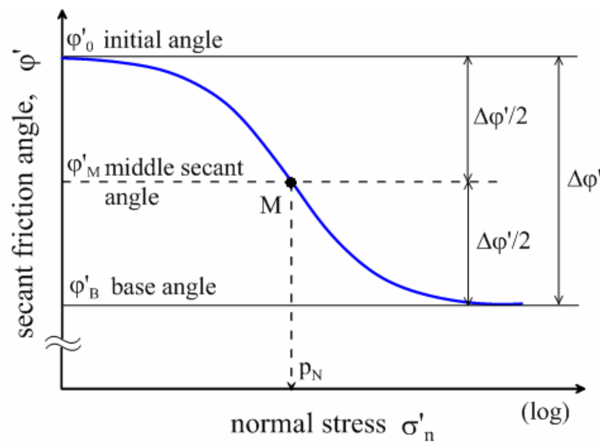

Figure 17. A mode of representing elements of a hyperbolic nonlinear failure envelope, $\varphi' = f(\log \sigma'_n)$ (Maksimović, 1989)

This form of the nonlinear failure envelope was considered using the same values of the mobilised cohesion. Also, the envelope that best agreed with the linear shear strength equation for loose compacted waste was the envelope obtained with the mobilized cohesion c'_{mob} = 10 kPa, i.e.:

$$\tau_f = 10.0 + \sigma'_n \cdot \tan\left(33 + \frac{20}{1 + \frac{\sigma'_n}{30}}\right) \tag{5}$$

For dense waste it is:

$$\tau_f = 10.0 + \sigma'_n \cdot \tan\left(35 + \frac{22}{1 + \frac{\sigma'_n}{60}}\right) \tag{6}$$

The results for both groups of samples are given in Figures 18-19.

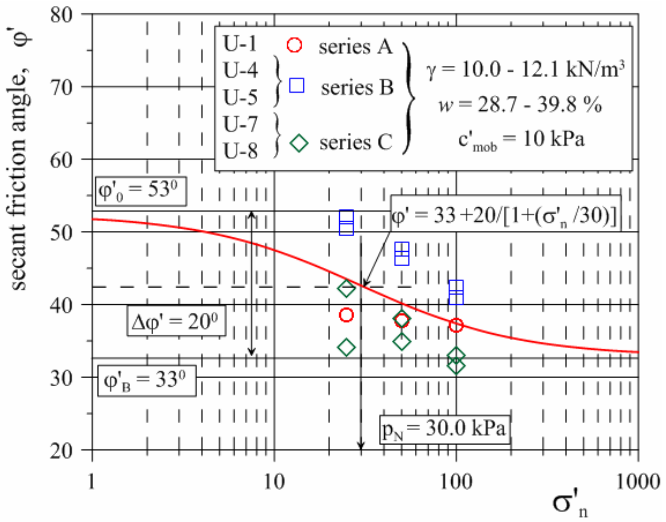

Figure 18. Nonlinear strength equation of hyperbolic shape for loose compacted waste.

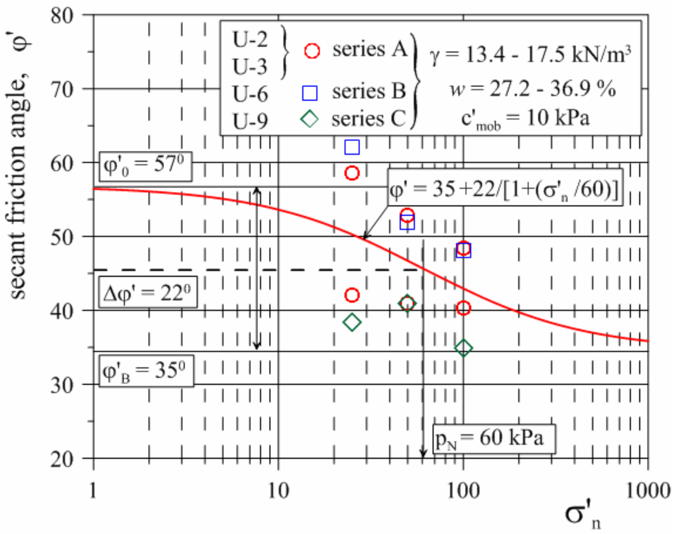

Figure 19. Nonlinear strength equation of hyperbolic shape for dense waste.

The resulting nonlinear failure envelopes are compared with the linear Coulomb-Mohr-Terzaghi equation and the logarithmic equation proposed by Zekkos (2005) and shown in Figure 20.

The logarithmic shape of the nonlinear envelope fitted in the range from 25 kPa to 100 kPa of the applied normal effective stresses (σ'_n), but differed for stresses higher than $\sigma'_n > 100$ kPa in giving lower values of the angle of internal friction, or of the shearing resistance.

The proposed hyperbolic shape of the nonlinear failure envelope fitted a somewhat wider range of normal stresses (σ'_n) from 20 kPa to 150 kPa. Moreover, it clearly indicated that compared with the logarithmic envelope it agrees much better with the linear Coulomb-Mohr-Terzaghi envelope due to the wider range of normal stresses.

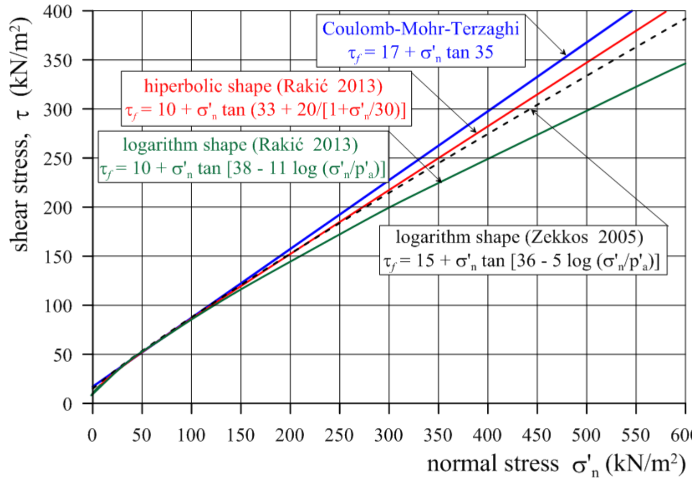

Figure 20. Comparative review of proposed linear and non-linear shear strength envelope of municipal waste material in Serbie

5 CONCLUSIONS

Conventional methods used in soil investigations are practical for research of the highly heterogeneous municipal solid waste. The values obtained for the shearing resistance parameters are within the ranges found in published literature. Published data, however, are not to be directly used without preliminary knowledge of the composition of waste, pretreatment of the components, sample preparation and the component identification procedure.

The research resulting relations, whether linear (Coulomb-Mohr-Terzaghi) or nonlinear (logarithmic or hyperbolic shape), give satisfactory values for the shear strength that may be used to analyse slope stability of 10-15 m high landfills in Serbia for normal effective stresses $\sigma'_n < 150$ kPa. For higher landfills, the hyperbolic form of the nonlinear failure envelope is recommended, which gives somewhat lower shearing resistance values than the usual linear envelope. In view of the always lower than real shear strength values based on field data and back-analyses, use of nonlinear shearing resistance equation is still justifiable.

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