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Estimation of mountain slope stability depending on ground consistency and slip-slide resistance changes on impact of dynamic forces

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Abstract. In this paper, three types of clayish soils with different consistency and humidity properties and slip-slide resistance indexes are considered on impact of different cyclic shear stresses. The side-surface deformation charts are constructed on the basis of experimental data obtained testing cylindrical soil samples. It is shown that the fluctuation amplitude depends on time and the consistency index depends on the humidity condition in the soil inner contact and the connectivity coefficients. Consequently, each experiment is interpreted. The main result of this research is that it is necessary to make corrections in the currently active schemes of slip-hazardous slopes stability estimation, which is a crucial problem requiring ASAP solution.

1. Introduction

In consequent calculation systems, the real slope stability estimation can significantly be affected by changes of the slope soils resistance under the action of static or dynamic forces. One of the most important issues in engineering geology and soil mechanics is the determination of slip-slide resistance indexes of clayish soils on impact of static and dynamic forces. Note that the above-mentioned problem has not been illustrated properly in the few currently existing scientific papers [1–3]. The current construction norms define that, when estimating the slope stability in consequent calculation systems [4], the dynamic and seismic impacts should be considered together with additional inertial forces, but no possible deviations of the soil slip-slide resistance are mentioned in these norms.

The main goal of this work is experimentally to justify that, in some cases, it would be useful to take into account the changes in the soil slip-slide resistance initiated on dynamic impact when the real stability of the slope is estimated. To realize the above-mentioned goal, we shall investigate the sliding resistance characteristics in a wide range of conditions of cyclic changes in the slipping relative stress ($\tau/\tau_{f,st}$) and soil consistency (I_L).

2. Testing method

Three samples of clayish soils with different consistency and humidity properties taken at the Dilijan town International school mountain slope in Armenia were used. Comparing the hydro-physical properties of soils (table 1), one can see that the clayish soil samples consequently have



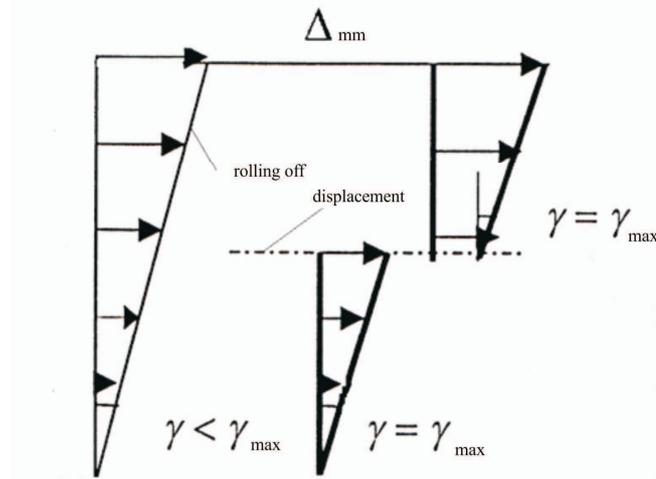


Figure 1. Dynamics of soil slip-deformation in the torsion test tool [5, 6].

Table 1. Experimentally determined hydro-physical indexes of soil samples.

Types	Specific gravity ρ g/cm ³	Soil humidity W	Mineral particles specific gravity ρ_s g/cm ³	Porosity coefficient e	Limits of plasticity			Consistency index $I_L = \frac{W - W_p}{W_L - W_p}$
					Liquid limit W_L	Plastic limit W_p	Plasticity index I_p	
1	1.98	0.155	2.67	0.579				0.045
2	1.95	0.186	2.67	0.644	0.281	0.149	0.132	0.280
3	1.89	0.245	2.67	0.759				0.727

1 — half-hard ($I_L = 0.045$), 2 — tight-plastic ($I_L = 0.280$), and 3 — soft-plastic ($I_L = 0.727$) consistency.

The soil tests were carried out for cylindrical samples with $d = 101$ mm and $h = 24$ mm. The samples were fixed in protecting rings of 2–4 mm height, which allowed tracing the process of slip-deformation.

Each sample participated in a specific dynamic process of slip-deformation during the testing [3, 5]:

- The soil hard, half-hard, tight-plastic ($I_L < 0.5$) consistency deformation under slip stresses up to τ_0 is manifested as aside-inclination (figure 1), but starting from $\tau_0 > \tau$, the critical deformation starts formation of a localized slip-zone, where the further process of slipping evolves (figure 1). Moreover, the soil does not deform above and below this zone.
- In the case of soft-plastic, flow-plastic ($I_L > 0.5$) consistency, at any value of the clayish soil deformation, the slip-stress takes place along the whole height in the form of aside-inclination according to Bingham–Shvedov viscous-plastic or Newton viscous body models [5, 6] (figure 1).

Experiments aimed at determining the clayish soil slip-stress resistance under static and dynamic forces were carried out using the upgraded M-5 torsion test tool (figure 2). In



Figure 2. Upgraded M-5 torsion test tool.

addition to the scrolling static moment, the tool also provides simultaneous action of stresses of frequency $f = 1\text{--}20$ Hz and shear alternating cyclic stresses of several values.

Five cyclic experiments with cylindrical test-samples of clayish soil were carried out according to the method described below.

First, the samples experienced the action of condensing normal stresses of magnitude $\sigma = 0.1, 0.2,$ and 0.3 MPa, respectively, and then the initial shear τ_0 stresses are applied of the following value for each experiment:

1-series (soil type: Nos. 1 and 2, half-hard, tight-plastic): $\tau_0 = 0.5\tau_{f,st}$ ($\tau_{f,st}$ is the soil shear standard resistance);

2-series (soil type: Nos. 1 and 2, half-hard, tight-plastic): $\tau_0 = 0.77\tau_{f,st}$;

3-series (soil type: Nos. 1 and 2, half-hard, tight-plastic): $\tau_0 = 0.81\tau_{f,st}$;

4-series (soil type: No. 3, soft-plastic): $\tau_0 = 0.4\tau_{f,st}$;

5-series (soil type: No. 3, soft plastic): $\tau_0 = 0.650\tau_{f,st}$.

In the whole, 45 experiments were carried out in 5 series, and each of them consisted of 9 experiments.

After stabilization of the slipping process, the samples undergo the action of shear dynamic alternating stresses of several frequencies whose values were equal to $\Delta\tau = \pm(\tau_{f,st} - \tau_0)$, and then the obtained data were registered after compilation in each 10, 30, 60, 120, and 360 seconds.

3. Interpretation and discussion of obtained data

Now let us interpret the experimental data only in 6 cases where the cylindrical soil test-samples experience the action of $\sigma = 0.2$ MPa = const (half-hard and tight-plastic soils) and $\sigma = 0.1$ MPa = const (soft-plastic soils) static normal stresses.

Figure 3 presents 6 charts of the time (t) dependence of the aside-deformation fluctuation amplitude of cylindrical test-samples. The data were registered after stabilization of the initial deformation on impact of several frequency cyclic $\pm\Delta\tau$ relative stresses ($\tau_0/\tau_{f,st}$).

According to figures 3a and 3c, which are plotted for half-hard soil No. 1 (table 1) and plastic type No. 2 (table 1), when $\sigma = 0.2$ MPa and $\tau_0/\tau_{f,st} = 0.5$, during the initial time of cyclic changing stresses, it is observed that the slipping deformation amplitude gradually increases. This means that the soil's ability to resist the shear decreases. Moreover, as the amplitude growth indicates, its intensity and the time also significantly depend on the soil type, and dynamic shear $\pm\Delta\tau$ stresses, on the amplitude influencing the test sample. Parallel to the

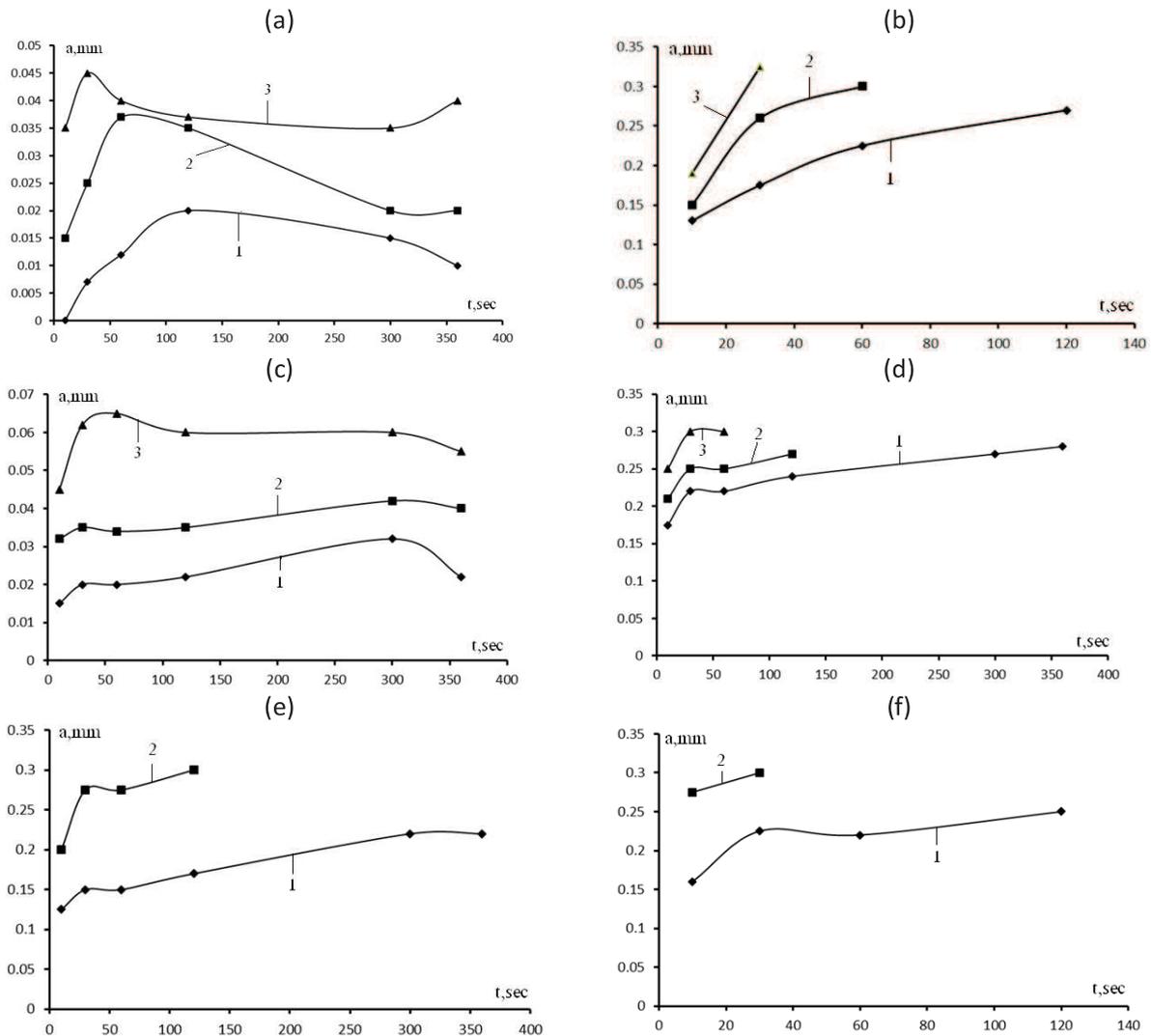


Figure 3. (a) and (b): half-hard soil’s physical properties for $I_L = 0.0465$ ($w = 0.155$), $\sigma = 0.2$ MPa (1 — $f = 8$ Hz, 2 — $f = 10$ Hz, 3 — $f = 12$ Hz); (c) and (d): tight-plastic consistency soil with $I_L = 0.280$ ($w = 0.186$), $\sigma = 0.2$ MPa (1 — $f = 8$ Hz, 2 — $f = 10$ Hz, 3 — $f = 12$ Hz); (e) and (f): soft-plastic consistency soil with $I_L = 0.720$ ($w = 0.255$), $\sigma = 0.1$ MPa (1 — $f = 6$ Hz, 2 — $f = 8$ Hz).

increase in the dynamic influence, a time decrease in slipping deformation amplitude is observed here, which is independent of the dynamic shear stress amplitude. Then, in the case of half-hard test-sample, when $f = 8$ Hz, the deformation decreasing process persists, but when $f = 10$ and 12 Hz, the deformation ascending trend is observed (figure 3a). The initial growth of the deformation amplitude is observed after the above-mentioned deformation value decreases, as the time increases, and then it decreases independently of the value of the frequency of shear stresses in the case of a tight-plastic soil (figure 3c). The shear deformation is expressed via the aside-inclination without formation of the localized shear zone and, at the end of experiment, no decrease in shear strength is observed on the surfaces of the above-mentioned two test samples.

Let us consider the cases where the half-hard and tight-plastic soil samples were tested for $\sigma = 0.2$ MPa under normal stresses. First, the stresses $\tau_0/\tau_{f,st} = 0.81$, $\tau_0/\tau_{f,st} = 0.77$

Table 2. Soil slipping resistance indexes obtained by processing the data in figure 4.

Soil Type No.	Humidity W	Index of consistency I_L	Coefficient of internal friction		Cohesion	
			Under static conditions, $\tan \varphi_{st}$	Under dynamic conditions, $\tan \varphi_{dyn}$	Under static conditions, C_{st} , MPa	Under dynamic conditions, C_{dyn} , MPa
1	0.155	0.045	0.421	0.379	0.018	0.015
2	0.186	0.280	0.338	0.257	0.016	0.013
3	0.245	0.727	0.224	0.124	0.018	0.005

were respectively implemented on these test-samples, then after stabilization of shear deformation $\pm\Delta\tau$, the cyclic shear strains were transmitted (figures 3b and 3d). According to these charts, the shear deformation amplitudes for these samples have the same qualitative character regardless of the frequency of the used transmitter. An increase in the cyclic tension can result in a monotonous increase in the dynamic deformation amplitudes of slide, leading to a decrease in the test-sample resistance to slip. Quantitative comparisons show that both the intensities of variations in the time of dynamic deformation and the durability of resistance to slip substantially depend on the range of soil and the frequency f of the dynamic torque (figures 1b and 1d).

Now let us consider the experimental data on the soft-plastic consistency of clayish soils (soil type No. 3; table 1; figures 3e and 3f). According to these charts in the case of above-mentioned two cyclic conditions due to the increased duration of dynamic stress, the slide amplitude grows practically monotonically, which finally leads to the end of the soil resistance to slip without formation of a localized shear zone. In the course of time, the intensity of the slide amplitude growth and the time of decrease in the resistance depend on the characteristic values of $\tau_0/\tau_{f,st}$ and $\pm\Delta\tau$, and f . In this case, the test-values $\sigma = 0.1$ MPa, the ratios $\tau_0/\tau_{f,st} = 0.4$ and 0.6 , and the frequencies of fluctuations of dynamic shear stresses $\pm\Delta\tau$ were, respectively, equal to $f = 6$ Hz and $f = 8$ Hz.

In the tests in the case of sliding resistance–normal tension dependence, all test-samples practically show linear functional independence of static or dynamic characteristics of the slip-stresses impact, as this is obvious from the charts in figure 4.

It is obvious that the values of the soil inner coefficient of internal friction and the connectivity values of slipping dynamic stress impact are significantly smaller than the same indexes under static conditions. This difference becomes more profound when the consistency index increases. So the differences for the inner contact indexes of half-hard, tight-plastic, and soft-plastic soils are, respectively, approximately about 21%, 24%, and 47%, and for connectivity, 17%, 19%, and 72%.

The data in table 2 and figure 4 allow one to obtain the following empirical expressions for the soil slipping resistance ($\tau_{f,st} = \sigma \tan \varphi + c$).

1. Half-hard consistency of soil: when ($I_L = 0.045$), then

$$\tau_{f,st} = 0.481\sigma + 0.018, \quad \tau_{f,dyn} = 0.379\sigma + 0.015.$$

2. Tight-plastic consistency of soil: when ($I_L = 0.280$), then

$$\tau_{f,st} = 0.338\sigma + 0.016, \quad \tau_{f,dyn} = 0.2657\sigma + 0.013.$$

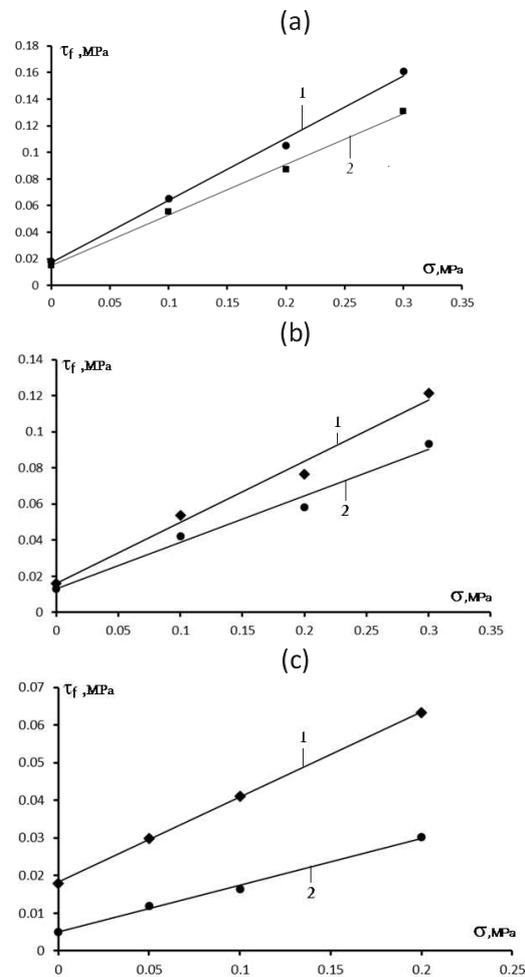


Figure 4. Relationship between the soil slip-resistance and condensing normal stresses. (a), (b), and (c) charts subject to half-hard, tight-plastic and soft-plastic consistent soils, respectively (1 — static experiments data, 2 — dynamic experiments data).

3. Soft-plastic consistency of soil: when ($I_L = 0.727$), then

$$\tau_{f,st} = 0.224\sigma + 0.018, \quad \tau_{f,dyn} = 0.124\sigma + 0.005.$$

Under the conditions of static and dynamic slipping stress impact, the charts of functional dependence between the clayish soil inner coefficient of internal friction ($\tan \varphi$), cohesion (C), humidity (W), and consistency (I_L) are presented in figure 5. These charts are based on the data given in table 2.

The obtained data, which are illustrated in figure 5, can be described sufficiently well by the following empirical expressions.

1. Inner coefficient of internal friction–consistency index dependence:

$$\tan \varphi_{st} = 0.4865e^{-1.094I_L}, \quad \tan \varphi_{dyn} = 0.4074e^{-1.637I_L}.$$

2. Inner coefficient of internal friction–humidity dependence:

$$\tan \varphi_{st} = 0.0216W^{-1.665}, \quad \tan \varphi_{dyn} = 0.004W^{-2.257}.$$

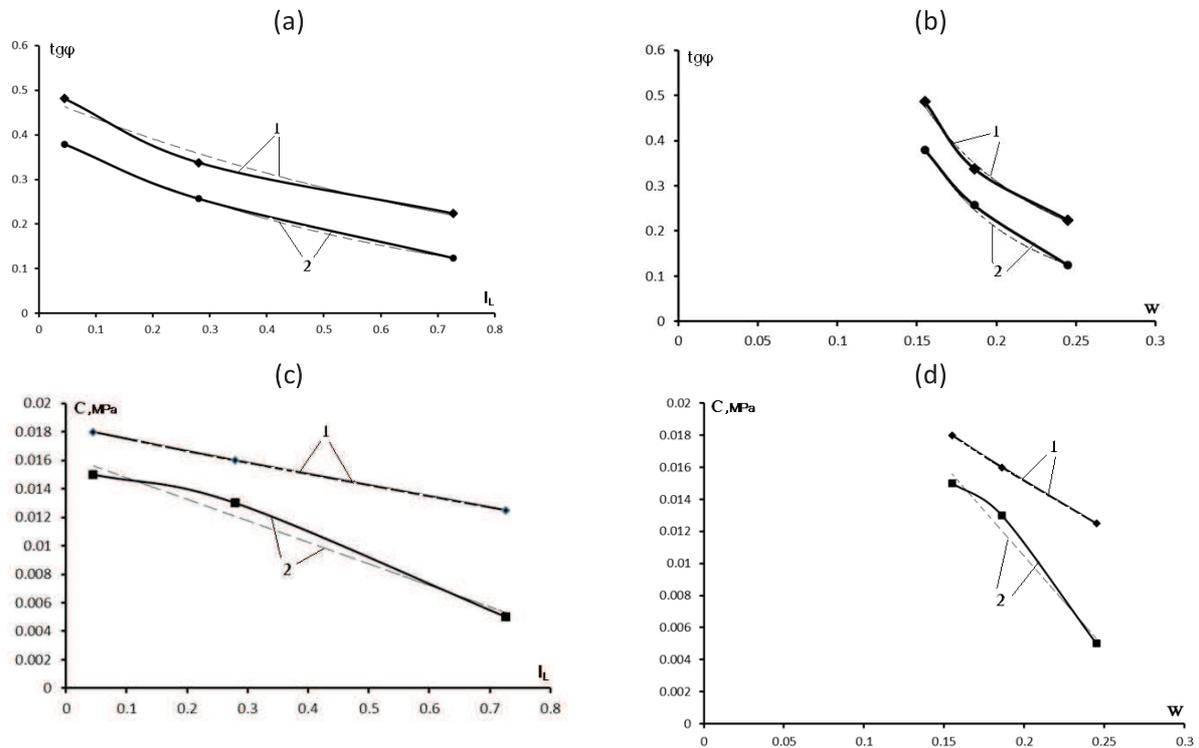


Figure 5. Dependence between: (a) soil inner coefficient of internal friction C and consistency I_L , (b) soil inner coefficient of internal friction $\tan \varphi$ and humidity W , (c) soil inner coefficient of internal friction $\tan \varphi$ and consistency I_L , and (d) cohesion C and humidity W under static (1) and dynamic (2) loadings.

3. Cohesion index–consistency index:

$$C_{st} = -0.0088I_L + 0.0184, \quad C_{dyn} = -0.0151I_L + 0.163.$$

4. Cohesion index–humidity index:

$$C_{st} = -0.0668W + 0.0284, \quad C_{dyn} = -0.1143W + 0.0333.$$

Conclusion

The variations in the slope fluctuations due to different causes can lead to a decrease in the ability to resist the slope whose value depends on the soil consistency index (I_L), the value of slide-relative static stresses ($\tau_0/\tau_{f,st}$), and the frequency (f) of the shear dynamic stress fluctuation ($\pm\Delta\tau$). Moreover, for

- $\tau_0/\tau_{f,st} < 0.7$ and $f < 12$ Hz, half-hard ($0 < I_L < 0.25$) and tight-plastic ($0.25 < I_L < 0.50$) soils, no consumption of resistance occurs in consistent soils;
- $\tau_0/\tau_{f,st} > 0.7$ and $f < 12$ Hz, consumption of resistance occurs in the above-mentioned soils, and the time of attaining this point decreases $\tau_0/\tau_{f,st}$ while the frequency (f) increases;
- $\tau_0/\tau_{f,st} > 0.4$ and $f > 6$ Hz, consumption of resistance occurs in the soft-plastic consistency soils ($I_L > 0.50$) and, in this case, the higher the values of ($\tau_0/\tau_{f,st}$) and f , the smaller the soil resistance to sliding.

Thus, on the basis of the results obtained in direct experiments and the above-described results, it can be concluded that to adjust the accuracy of calculations of the landslide slopes stability is a crucial problem which urgently requires to be solved. This problem can be solved by coordinating the well-known data and new researches aimed at this target.

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