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On Collapse-Settlement Calculations for Heterogeneous Collapsible-Soil Subgrade

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ABSTRACT

In a previous paper the authors have dealt with collapse-settlement calculations for embankments based on a homogenous collapsible soil subgrade. For this same subject the present paper represents modifications to the aforementioned collapse-settlement calculations to include in-situ cases of heterogeneous collapsible-soil subgrades. It is well known that collapsible soil deposits exhibit a high potential for collapse deformation under external loading. Evaluation of the collapse potential is, thus, required for settlement calculations relating to the base of embankments placed on a collapsible soil subgrade. The evaluation conducted leads to the conclusion that collapse potential is dependent upon the following parameters: (a) liquid limit, (b) plasticity limit, (c) in-situ dry density, (d) in-situ moisture content, and (e) applied pressure at wetting in the single-oedometer test. Knowledge of these parameters, together with that of the water-penetration depth into the subgrade stratum and the effect of partial saturation on a reduction of the full collapse potential, is shown to enable a calculation of the amount of collapse-settlement in a heterogeneous stratum.

Keywords: Collapse, Embankment, Heterogeneous subgrade, Settlement, Silty-characteristics

1. INTODUCTION

In a previous paper [1] the authors have dealt with collapse-settlement calculations for embankments based on a homogenous collapsible soil subgrade. It is well known, however, that collapsible soil deposits, found extensively in many arid and semi-arid regions of the world, are not necessarily of a homogenous nature. Thus, modifications to the above collapse-settlement calculations to include in-situ cases of heterogeneous collapsible-soil subgrades are necessary.

To recall, upon loading, all soils settle, but the amount of settlement varies from soil to soil and is dependent on load-induced stresses. Although such settlement will eventually cease after a certain period of time, subsequent wetting under certain conditions may cause additional settlement, known as collapse. An evaluation of a soil's collapse potential should, thus, be included in all settlement calculations. In this paper, the base of embankments placed on a collapsible soil subgrade provides the objective of these calculations.

Two methods currently exist to determine the amount of collapse in the laboratory, the single-oedometer test and the double-oedometer test. This paper refers only to the single-oedometer test, known also as ASTM D 5333 collapse testing. In this test, an undisturbed or remolded specimen is first driven into the oedometer ring and then subjected to increasing vertical load. The specimen is permitted to attain equilibrium deformation at each level of pressure. It is then inundated at a prescribed applied pressure, and the deformation is measured. The deformation induced by the addition of water, divided by the initial height of the specimen, expressed in percentage terms, defines the collapse potential, which this paper also terms vertical collapse.

Now, a prediction of the settlement of the base of an embankment as a result of added water, and thus as a result of subgrade collapse, necessitates knowledge of the collapse-pressure characteristics (curves) of the silty stratum under consideration. These curves, which are usually obtained from laboratory tests on undisturbed and remolded silty samples, are in general terms dependent on the following parameters: (a) liquid limit, (b) plastic limit, (c) in-situ moisture content, and (d) in-situ dry density. In light of all these introductory notes, the objectives of this paper are as follows:

- Presentation of measured data of heterogeneous collapsible-soil subgrade as collected from a recent railway project located in the southern part of Israel.
- Describing the accepted collapse model of the previous paper [1] and comparing its output for the data measured in the aforementioned railway project.
- Formulating the effect of partial saturation on collapse potential and evaluating the in-situ saturation distribution from wetting a heterogeneous stratum.
- Outlining the suggested collapse-calculation procedures for any given site conditions of heterogeneous nature.

Finally, through an Excel spreadsheet, the paper offers a practical example of how the suggested collapse calculation can be applied with any given set of data.

2. HETEROGENEOUS STRATA EXAMPLE

As mentioned previously, collapsible soil in-situ deposits are in most cases of a heterogeneous nature. Presentation of such a stratum example as measured in a recent railway project located in the southern part of Israel is given in this section. Fig. 1 shows the plasticity characteristics of the tested samples for their collapse potential given in Fig. 2.

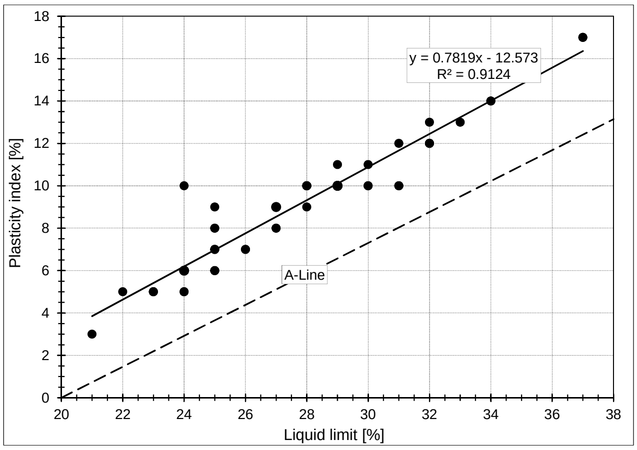

Figure 1: Plasticity data from silty specimens taken from the discussed railway project

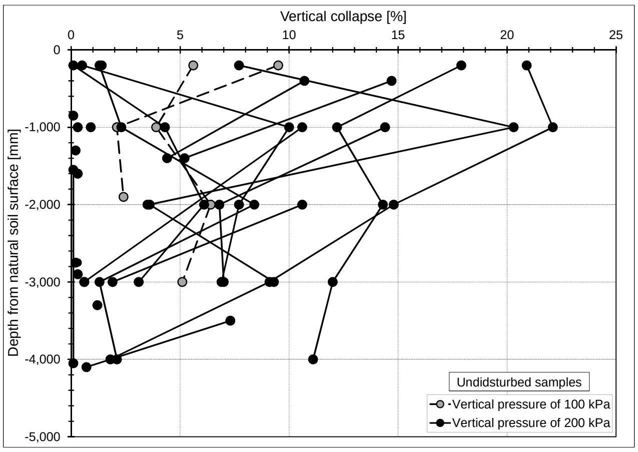

Figure 2: Rate of collapse versus depth from subgrade's surface for the silty specimens of Fig.1

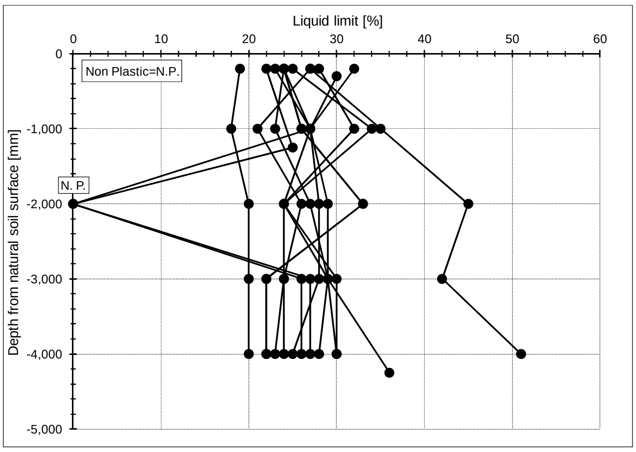

Figure 3: Liquid limit versus depth from subgrade's surface as measured at several borings in the silty stratum of Fig. 1

In addition to Figs. 1 and 2, Figs. 3, 4, 5, and 6 describe for the silty subgrade the variations of the following with depth: liquid limit, plasticity limit, in-situ moisture content and in-situ dry density. These figures represent only the borings for which full results are available.

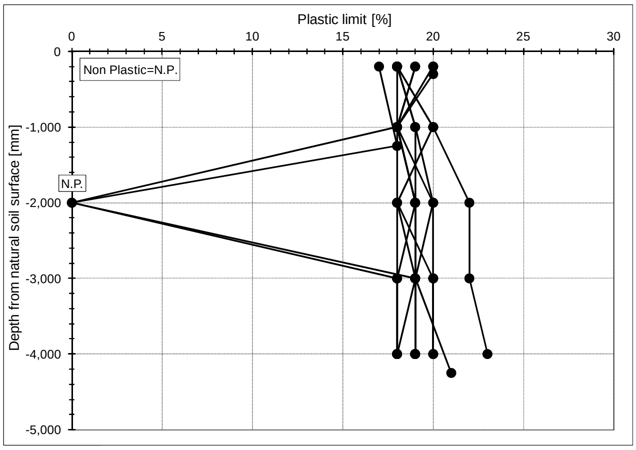

Figure 4: Plasticity limit versus depth from subgrade's surface as measured at several borings in the silty stratum of Fig. 1

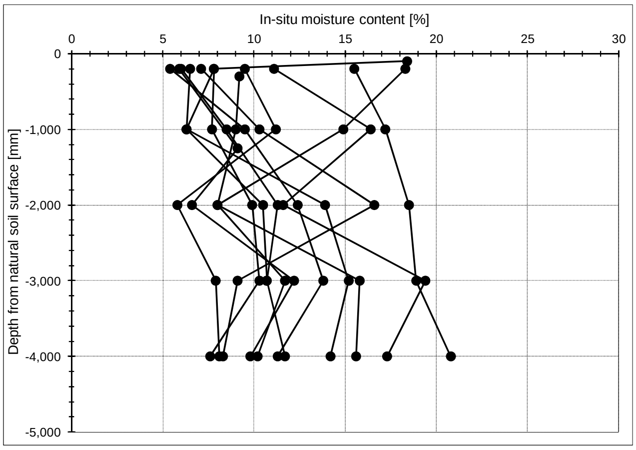

Figure 5: In-situ moisture content versus depth from subgrade's surface as measured at several borings in the silty stratum of Fig. 1

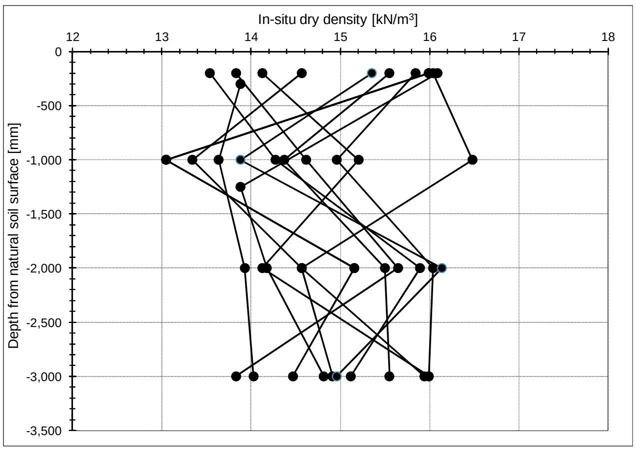

Figure 6: In-situ dry density versus depth from subgrade's surface as measured at several borings in the silty stratum of Fig. 1

All the above figures demonstrate the remarkable heterogeneity that characterizes the silty stratum of the above given project. As indicated by the figures, this heterogeneity varies both with location (i.e., from one testing point location to another) and depth. Thus, the existence of this heterogeneity should govern the required collapse calculations.

3. VERTICAL COLLAPSE MODEL

Predicting the settlement of an embankment-base surface as a result of subgrade collapse necessitates knowledge of the collapse-pressure characteristics (curves of the collapse model) of the silty stratum under consideration, and these are usually obtained from laboratory tests on undisturbed silty samples. This prediction model denotes a statistical relationship between the vertical collapse (Cp), in percentage, that is due to applied vertical pressure (Pp) in kPa, and the following parameters characterizing the silty specimens under examination: in-situ moisture content (W) in percentage, in-situ dry density (D) in kN/m^3 and dry density at liquid limit (D_{LL}) in kN/m^3 as defined by Eq. (2). According to [1] the vertical collapse model formulation is as follows:

$$Cp=28.5354-27.0305\times(D/D_{LL})^{0.9825}+ \\ +0.0001196\times[\log(Pp)]^{11.3741}/(W/PL)^{1.4908} \quad (1)$$

$$D_{LL}=9.807\times100/(100/G+LL) \quad (2)$$

In Eq. (2), G denotes the solid specific gravity of the silty specimen, LL denotes its liquid limit in percentage, and PL denotes its plasticity limit in percentage. Note that Eq. (1) was formulated to yield the highest R^2 value from among all possibilities that (a) include the independent variables of the soil's plasticity and (b) yield true physical behavior as clearly described in [2] (i.e., an increase in Cp with increasing Pp, and a decrease in Cp with increasing W, D and LL). The D/D_{LL} variable of Eq. (1) exactly follows this finding as given in [3] or indirectly as given by a similar finding in [4].
Fig. 7 depicts the graphical presentation of Eq. (1) together with the collapse data as measured for the project described in the previous section. This figure indicates a reasonable compatibility between the measured and calculated data.

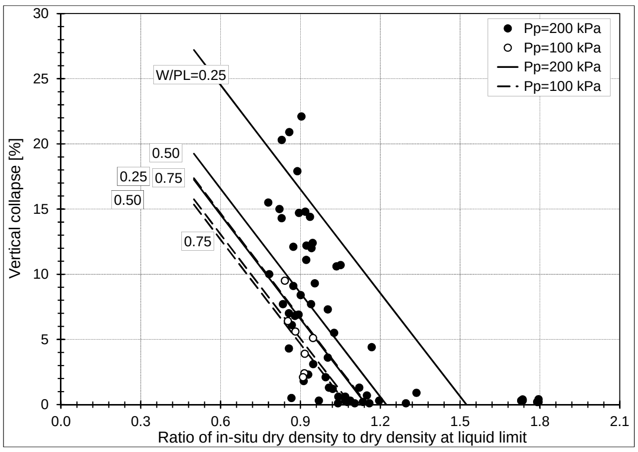

Figure 7: Vertical collapse versus density ratio (D/D_{LL}) for vertical pressures of 100 kPa and 200 kPa as derived from Eq. (1) for the experimental data of Fig. 2

4. EFECT OF PARTIAL WETTING

Partial wetting of the specimens in the single-oedometer test results in only a proportion of the total collapse value that is compatible with the case of total specimen inundation. The study conducted in [6] indicates that full collapse essentially occurs for degrees of saturation of 65%-70% and above. However, for degrees of saturation of 50%, only about 85% of the full collapse occurs.
Fig. 8, reproduced from Fig. 14 in [6], enables formulation of the aforementioned collapse reduction resulting from partial saturation. The equations obtained are the following:

$$Ro=-6.95\times(\Delta So)^3+7.20\times(\Delta So)^2-0.20\times(\Delta So)-0.004151 \quad (3)$$

$$\Delta S_O=(S_F-S_I)/(100-S_I) \quad (4)$$

In Eq. (3), Ro denotes the collapse reduction; i.e., the ratio of vertical collapse resulting from a partially saturated state to the full vertical collapse resulting from a fully saturated state. ΔSo denotes the ratio increase in the degree of saturation from wetting as defined by Eq. (4). In the latter equation, S_I denotes the initial degree of saturation (prior to wetting) in percentage and S_F denotes the final degree of saturation (after wetting) in percentage.

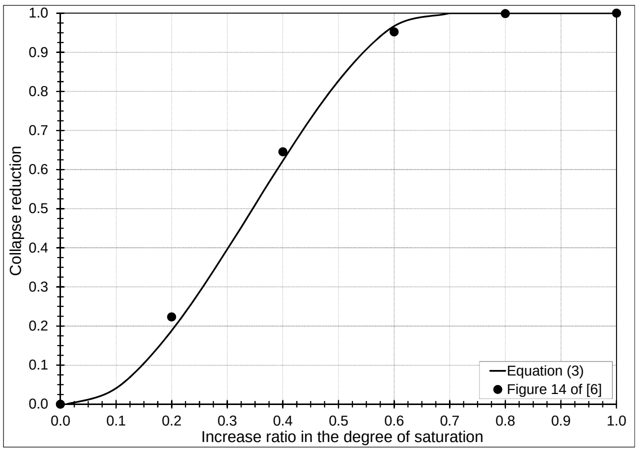

Figure 8: Collapse reduction (Ro) versus increased ratio in the degree of saturation (ΔSo), after [6]

The calculation of collapse for field conditions should obviously take into consideration the distribution of the degree of saturation with depth after wetting. According to [7], the depth of a change in moisture content occurring in the silty subgrade of an unpaved shoulder in a semi-arid zone resulting from a cumulative total of 300 mm rainfall per year extends down to 2,000 mm only. Fig. 8 depicts this moisture distribution as reported in [7].
An analysis of the aforementioned distribution with the aid of Eq. (5) and Eq. (6) leads to the conclusion that a good correspondence exists between the amount of effective rainfall that has penetrated into the silty subgrade and the characteristics of the moisture distribution shown in the figure.
The same pattern of moisture-content or degree of saturation distribution is reported in [5]. This reference deals with a

full-scale test in which artificial wetting (by ponding the site) is applied to cause settlement collapse in a silty stratum possessing a single concrete footing on its surface. For this test, the degrees of saturation monitored before and after wetting are given in Fig. 10, in which the degree of saturation distribution, as suggested by this paper for design purposes, is also included.

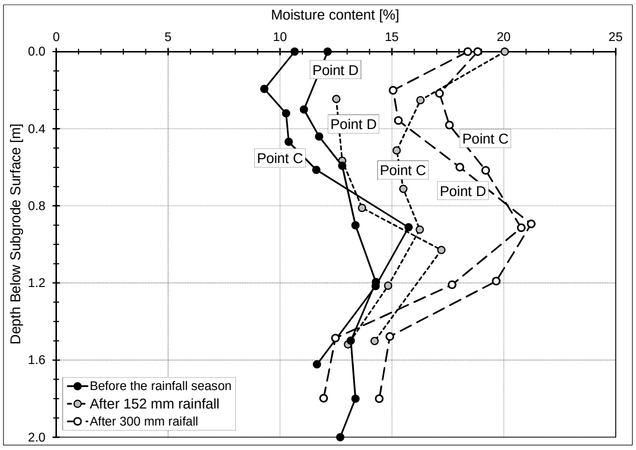

Figure 9: Moisture-content versus depth as measured in a silty subgrade from an unpaved shoulder of a flexible pavement, after [7]

In addition, the data in [6] also includes in-situ moisture-content distribution before and after artificial wetting. Figs. 9-11 in this reference indicate that the general pattern of moisture-content distribution or the degree of saturation distribution in Fig. 9 or Fig. 10 also exists in these figures.

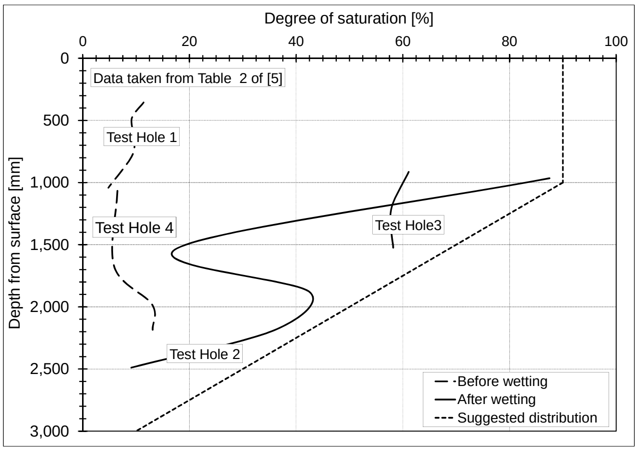

Figure 10: Degree of saturation versus depth as measured in the collapse field test of [8]

5. SETTLEMENT CALCULATIONS

The first step in calculating the settlement of an embankment base constructed on heterogeneous silty subgrade is to evaluate S_F and ΔSo from the rainfall quantity together with the final moisture distribution as described in Fig. 10. This calculation is performed with the aid of the following equations:

$$W_{FM}=100\times H_W/(Z_F\times D_{IM}/9.807)+W_{IM} \quad (5)$$

$$W_{FT}=2\times Z_F\times(W_{FM}-W_{IM})/(Z_C+Z_F)+W_{IM} \quad (6)$$

$$S_{IM}=100\times W_{IM}/(100\times 9.807/D_{IM}-100/G) \quad (7)$$

$$S_{FT}=100\times W_{FT}/(100\times 9.807/D_{FM}-100/G) \quad (8)$$

In these equations, W_{IM} denotes the initial moisture content in percentage, equals to the average value of the existing ones along the depth of the active zone, W_{FM} denotes the average final moisture content along the wetted zone in percentage, W_{FT} denotes the final moisture content at the bottom of the upper compacted subgrade layer in percentage, Z_F denotes the depth of active (wetting) zone in mm (i.e., usually 3,000 mm; see Figs. 9 and 10) measured from the bottom of the upper compacted subgrade layer, Z_C denotes the depth of the constant wetting region measured from the bottom of the upper compacted subgrade layer subgrade in mm (i.e., usually 1,000 mm; again see Figs. 9 and 10), H_W denotes the effective rainfall quantity that penetrates into the uncompacted subgrade in mm, D_{IM} denotes the dry density of the silt before wetting in kN/m^3, equals to the average value of the existing ones along the depth of the active zone, D_{FM} denotes the dry density of the silt after wetting in kN/m^3, equals to the average value of the existing ones along the depth of the active zone (assumed also to be equal to D_{IM}), G denotes the solid specific gravity of the silt, S_{IM} denotes the average initial degree of saturation (prior to wetting) in percentage, and S_{FT} denotes the final degree of saturation (after wetting) at the top of the subgrade in percentage. Note that these equations refer to a heterogeneous silty stratum in regard to liquid and plasticity limits, in-situ water content and in-situ dry density.

Now, for the range of subgrade depth (Z_i) of 0 to Z_C mm, the increased ratio in the degree of saturation (ΔS_{OT}) that is due to wetting is:

$$\Delta S_{OT}=(S_{FT}-S_{IM})/(100-S_{IM}) \quad (9)$$

For the range of subgrade depth (Z_i) of Z_C mm to Z_F mm, the increased ratio in the degree of saturation (ΔS_{OZ}) that is due to wetting at a depth of Z_i in mm is:

$$\Delta S_{OZ}=\Delta S_{OT}\times(Z_F-Z_i)/(Z_F-Z_C) \quad (10)$$

The development of Eqs. (9) and (10) enables a computation of settlement resulting from rain water penetration into the uncompacted silty stratum for any given in-situ data. This computation is performed by dividing the uncompacted silty stratum into horizontal strips of 500 mm thickness down to a depth of Z_F) (i.e., usually, again, 3,000 mm). The final computed settlement (δ) for a heterogeneous silty stratum is derived from the following equation:

$$\delta=\Sigma(Roi\times Cpi\times 500)/100 \quad (11)$$

Where: Roi denotes the collapse reduction for the middle depth of the ith horizontal strip measured from the upper one, and Cpi denotes the vertical collapse in percentage, again for the middle depth of the ith horizontal strip. Note that Cpi is calculated according to Eq. (1) when for each ith horizontal strip its measured in-situ values of in-situ moisture content, in-situ dry density, liquid limit and plasticity limit ate applied. Now, for each horizontal strip the vertical pressure (Ppi) is given by the following equations:

- For the first horizontal strip:

$$Pp_1=H_E\times D_E+H_C\times D_C+H_P\times D_P+250\times D_1\times(1+W_1/100) \quad (12a)$$

- For the second horizontal strip:

$$Pp_2=Pp_1+250\times D_1\times(1+W_1/100)+250\times D_2\times(1+W_2/100) \quad (12b)$$

- For the ith horizontal strip:

$$Pp_i=Pp_{i-1}+250\times D_{i-1}\times(1+W_{i-1}/100)+250\times D_i\times(1+W_i/100) \quad (12c)$$

Where: H_E denotes the height of the given embankment in mm, D_E denotes the wet in-situ density of the embankment in kN/m^3, H_C denotes the thickness of the upper compacted subgrade layer in mm, D_C denotes the wet in-situ density of the upper compacted subgrade layer in kN/m^3, H_P denotes the thickness of the given pavement in mm, D_P denotes the wet in-situ density of the pavement in kN/m^3, and Ppi denotes the vertical pressure acting at the middle thickness of the ith horizontal strip in kPa.

In all the above calculations the upper compacted subgrade layer has been excluded from the subgrade stratum. This exclusion derives from the fact that silty layers when compacted lose their entire collapsible characteristic. Moreover, these layers assist in reducing the amount of water penetration into the uncompacted subgrade, and thus they assist also in reducing the collapse deflection rate.

The best way to demonstrate the settlement computation is by presenting a specific illustrative example. This was done with the aid of the Excel spreadsheet shown in Fig. 11 for (a) the data written with italic fonts in the uncolored cells of the figure and (b) the collapse model formulated by Eq. (1).

To emphasize, the computations given in Fig. 11 assume these distribution inputs for the rainfall and moisture: H_W=150 mm,

Base-Settlement Calculations

Spreadsheet for Embankements & Hetrogeneous Strata

Design Input for Embankement, Compacted Subgtrade, and Pavement

Height of Embankement [mm]	*12,000*	*Thickness of Pavement [mm]*	*600*	*Wet Density of Fill Material [kN/m^3]*	*18.7*
Wet Density of Pavement [kN/m^3]	*22.7*	*Thickness of Compaction [mm]*	*600*	*Wet Density of Compacted Subrade [kN/m^3]*	*16.0*

Rainfall, Moisture, and Density Data per Season

Effective Rainfall per Year [mm]	*150*	*Depth of Active Zone [mm]*	*3,000*	*Depth of Uniform Moisutre [mm]*	*1,000*
Aver' In-Situ Moisture Content [%]	9.9	Aver' In-Situ Dry Density [kN/m^3]	14.6	Calculated Increase in Top Saturation [%]	0.24

Calculations			*Input Subgrade Data*				Calculations				
Depth from Bottom of Compacted Subgrade to the Midlle Depth of Horizontal Strip	Vertical Pressure on Middle of Horizontal Strip	Full Vertical Collapse	*Liguid Limit*	*Plasticity Limit*	*In-Situ Moisture Content*	*In-Situ Dry Density*	Calculated Intercept Value	Calculated Slope Value	Calculated Ratio Increase in Saturation	Final Partiall Vertical Collapse	Amount of Predicted Setllement
[mm]	[kN/m^{2}]	[%]	*[%]*	*[%]*	*[%]*	*[kN/m^3]*	[---]	[---]	[%]	[%]	[mm]
250	242.3	4.8	*35*	*17*	*10.5*	*14.5*	0.0414	0.0002	0.24	1.3	7
750	250.4	7.0	*33*	*18*	*8.5*	*15.3*	-0.6752	0.0004	0.24	1.9	9
1,250	258.7	7.3	*32*	*19*	*10.0*	*15.0*	0.2935	0.0003	0.21	1.5	8
1,750	266.7	9.2	*34*	*19*	*9.5*	*14.1*	1.1955	0.0003	0.15	1.0	5
2,250	274.5	9.1	*34*	*20*	*10.2*	*14.3*	0.8146	0.0003	0.09	0.3	1
2,750	282.4	8.4	*35*	*20*	*10.5*	*14.5*	0.0414	0.0003	0.03	0.0	0
3,250	290.5	8.2	*36*	*21*	*11.0*	*14.7*	-0.7423	0.0003	0.00	0.0	0
3,750	298.7	7.3	*37*	*21*	*11.5*	*14.9*	-1.5364	0.0003	0.00	0.0	0
4,250	307.1	7.0	*38*	*22*	*12.0*	*15.1*	-2.3409	0.0003	0.00	0.0	0
4,750	315.6	6.1	*39*	*22*	*12.5*	*15.3*	-3.1558	0.0003	0.00	0.0	0

Sum of Predicted Settlements [mm] **30**

Figure 11: An Excel spreadsheet designed for a heterogeneous stratum, demonstrating a settlement computation for the data given in the figure

Z_C=1,000 mm and Z_F=3,000 mm. The final settlement result is 30 mm, which is an acceptable value for withstanding the collapse event, when the permissible values of the Israeli guidelines for the swelling heave case [9] are also utilized for the collapse deformation case.

Now, the question arises as to which input parameters of the silty stratum should the above collapse calculations refer. Some agencies suggest implementation of the following taken from the total soil-exploration test results for a given project: (a) 15 percentile of the liquid limit value, (b) 15 percentile of the plastic limit value, (c) 15 percentile of the in-situ moisture content value and (d) 15 percentile of the in-situ dry-density value. In this context, however a recent study [10] showed that this kind of implementation can lead to unrealistic results.

Therefore, in light of the above, it is suggested to adopt an alternative option in which use is made of the 85-percentile criterion for all calculated collapse settlements for the real data of each given boring, being a function of location and depth (and not for the total 15 percentile values of the measured data).

6. SUMMARY AND CONCLUSIONS

This paper dealt with the issue of calculating collapse settlement, specifically that of the base of an embankment constructed on a heterogeneous collapsible silty subgrade. An essential input for this type of calculation, in addition to such routine characteristics as liquid limit, plasticity limit, in-situ moisture content and in-situ dry density, is an evaluation of the collapsing characteristics of the silty stratum; that is, the vertical collapse percentage.

It was shown that for a given set of experimental results on undisturbed silty specimens, Eq. (1) constitutes a reasonable collapse model. This model includes plasticity, moisture content and dry density inputs together with the vertical pressure rate acting on the given silty specimen.

In addition, it should be recalled that the collapse model is based on experimental results obtained from ASTM D 5333 collapse testing (also known as single-oedometer testing). Therefore, this model is compatible only with a final wetting state of full saturation. However, it was shown that only a final state of partial saturation is reached. The influence of this partial final site condition state on vertical collapse values is very significant as shown in Fig. 8 taken from [6]. Thus, the formulation of the curve given in this figure yields an important input for the settlement calculations discussed.

In order to utilize the reduced vertical collapse resulting from partial saturation, the depth of the wetting zone and the degree of saturation distribution along this zone should be evaluated. This was done in this paper by analyzing three different site tests reported in the technical literature [6, 7 and 8]. Moreover, it was found that the amount of effective rainfall that penetrates into the subgrade governs the characteristics of this distribution.

The final conclusion is that all the above findings can serve as a proper tool for calculating the collapse settlement of the base of an embankment constructed on a heterogeneous collapsible silty subgrade. This is illustrated in this paper by utilizing an Excel spreadsheet for a given practical example of a heterogeneous silty stratum. Using this spreadsheet and following the method suggested in [10] it is seems logical to adopt the option in which the 85-percentile criterion for all calculated heaves for the real silty characteristics of each given bore-hole is the governing one.

7. ACKNOWLEDGEMENTS

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