

# Swelling soils in the road structures

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**Abstract.** There are frequent problems with the soil swelling in the road construction in the past time. This phenomenon is known for decades. This situation is notably given by insufficient knowledge of this problem and difficulties with input parameters describing the swelling process. The paper in the first part proposed regression relations to predict swelling pressure, time of swelling and swelling strain for different initial water contents for soils and improvement soils. The relations were developed by using artificial neural network and QCExpert Professional software (on the data from site investigations by GeoTec-GS, a.s. and experimental data from CTU in Prague). The advantage of the relations is based on using the results of the basic soil tests (plasticity index, consistency index and colloidal activity) as input parameters. The authors inform the technical public with their current knowledge of the problems with the soil swelling on the motorway in the second part of the paper.

## 1. Introduction

The swelling is a complicated phenomenon affected by a many parameters from mineralogical composition and physically-chemical properties over basic physical property to the influence of the existing surcharge pressure and the type of used material (lime or cement etc.) in the case of soil stabilization.

The conditions needed for a swelling-susceptible soil to swell are the following:

- Stress relief in the soil body (this is always fulfilled for cut slopes) and/or
- water availability in the environment. This may or may not be fulfilled depending on circumstances.

The swelling is tested under laboratory conditions on undisturbed soil samples, usually only linear swelling is tested. Alternative procedure is to measure deformation in time in the oedometer while also measuring the swelling pressure. However, testing in stand with dynamometers where both swelling pressure and deformation are measured in time seems to be the best way to test swelling. The problem is that this test gives the values of the swelling pressure for the given initial state of the soil. But we also have to be interested in the swelling pressure for lower initial water content, because we cannot guarantee that such conditions will not occur in reality. When we focus on the swelling significance in transport engineering and its complexness (influence cut slope stability, destructive effects on pavements, the correct way of soil improvement etc.) the problems with test are clear. The duration of the test is between 160 and 210 hours. Therefore, the laboratory has to be sufficiently equipped for this type of time demanding testing and the cost of tests is also significant. If there are any criteria for





swelling in technical standards, it is only for linear swelling. But these values do not give any information about the swelling pressure (deformation is only an accompanying effect). It is shown that the swelling pressure varies with different initial conditions while the deformation may still be the same 3%.

## 2. Predicting the swelling properties

The swelling is a complicated phenomenon and prediction of the swelling parameters cannot take the account of all effects (especially mineralogical). The direct methods provide physical measurements of swelling pressure and are not suitable for quick identification of expansive soils [1]. For the example testing in stand with dynamometers where both swelling pressure and deformation are measured in time. Because of simplicity usually only linear swelling is tested and so the relative deformation is obtained only. The problem is that this test gives the values of the swelling pressure for the given initial state of the soil (i.e. initial water content). The variations of the shear parameters of soils at swelling with different initial moisture are evident in the Table 1 - there are larger differences in the effective shear parameters for lower initial (immediate) water content ( $w_L = 55\%$ ,  $w_n = 18\%$ ,  $I_p = 37\%$ ,  $I_a = 1.61$ ). In the Table 2 it is shown that the swelling pressure varies with different initial conditions (the initial moisture is significant) while the deformation may still be the same 3%.

The indirect methods are based on experience and basic soil parameters and produce quick and reliable identification of expansive soil. There are some empirical equations reported by various author in the literature - summary of some criteria for identifying swell potential is e.g. in [2]. One of the oldest is that of [3]:  $S = 3.6 \times 10^5 A^{2.44} C^{3.44}$  where  $S$  is the swell percent value under 1 psi (6.89 kPa),  $C$  is the percent of clay fraction and  $A = I_p/C$  where  $I_p$  is plasticity index. The other widely used equations were developed e.g. by [4] or [5].

**Table 1.** Selected geotechnical parameters for the different moisture.

	Immediate moisture $w_n$ (%)		
	12.0	23.0	30.0
Consistency index $I_c$	1.16	0.86	0.68
Swelling pressure $\sigma_b$	480	285	185
Relative deformation $\epsilon_b$ (%)	5.50	2.48	1.75
Peak effective friction angle $\phi_{ef,p}$ (°)	21.8	20.1	18.8
Peak effective friction angle at swelling $\phi_{ef,p,s}$ (°)	17.5	18.9	18.0
Difference at friction angle (%)	20.0	6.0	4.2
peak cohesion $c_{peak}$ (kPa)	29.6	23.8	19.9
peak cohesion at swelling $c_{p,l}$ (kPa)	16.3	20.2	17.6
Difference at cohesion (%)	45.0	15.0	11.5

To investigate the relationship between the soil index properties (plasticity index  $I_p$ , consistency index  $I_c$ , colloidal activity index  $I_a$ ) and the swelling pressure, time of swelling, and swelling strain it was performed analysis using regression on the large data sets from geological investigation of the many constructions in the Czech and Slovak Republic (tuffaceous clays, mudstones, claystones, chalk marlites and neogene clays). The best equations for swelling pressure, time of swelling and swelling strain are the follows:

- Predicted swelling pressure of the soil:

$$\sigma_{swel} = 0.0552 \cdot I_p^{2.385} \cdot I_c^{1.757} \cdot I_a^{0.397} \quad [\text{kPa}] \quad (1)$$

where:  $I_p$  - plasticity index [%],  $I_c$  - consistency index [-] and  $I_a$  -, colloidal activity index [-].



Note: the higher the water content of the soil (higher the consistency index for given plasticity index and colloidal activity index), the higher the swelling pressure.

- Predicted swelling strain:

$$\varepsilon_{swel} = 0.3 \cdot I_p^{0.2} \cdot I_c^{0.3} \cdot \sigma_{swel}^{0.3} [\%] \quad (2)$$

where:  $I_p$  - plasticity index [%],  $I_c$  - consistency index [-],  $I_a$  - colloidal activity index [-] and  $\sigma_{swel}$  - predicted swelling pressure [kPa].

Note: Considering  $\varepsilon_{swel} = \Delta h / H_v$ ; if the surface deformation in centimeters is known and the swelling is completed, we may determine (or rather estimate) the thickness of the swelling layer  $H = \Delta h / (0.01 \cdot \varepsilon_{swel})$ .

- Predicted time of swelling:

$$t_{swel} = 0.0013 \cdot H_v \cdot I_p \cdot 78.817 \cdot e^{\left( \frac{-4.493}{I_c^{1.3}} \right)} [\text{months}] \quad (3)$$

where:  $I_p$  - plasticity index [%],  $I_c$  - consistency index [-] and  $H_v$  - thickness of the swelling layer [cm].

Note: the swelling in this case is considered with water uptake from both sides. In reality, the water may be available only from one side and the swelling time may therefore be longer.

**Table 2.** Swelling pressures at relative deformation 3% for different soils.

Natural water content $w_n$ (%)	Water content at liquid limit $w_L$ (%)	Water content at plastic limit $w_p$ (%)	Soil particles < d <sub>0.002</sub> mm (%)	Plasticity index $I_p$ (%)	Consistency index $I_c$ (-)	Colloidal activity index $I_a$ (-)	Swelling pressure $\sigma_b$ (kPa)	Relative deformation due to swelling pressure $\varepsilon_b$ (%)	Difference between max. swelling pressure and actual value of swelling pressure (-)	Percentual difference between max. swelling pressure and actual value of swelling pressure (%)
32	58.7	18	15	40.7	0.66	2.71	270	3	0	0
23	51.8	16.4	20	35.4	0.81	1.77	238	3	32	11.7
22	52.4	23.8	17	28.6	1.06	1.68	225	3	45	16.7
38	71.6	33.4	59	38.2	0.88	0.6	213	3	57	20.9
20	53.6	24.9	36	28.7	1.17	0.8	200	3	70	26

### 3. Soil improvements and swelling

Soil modification by lime is very common. Lime significantly reduces swelling but for high values of plasticity index and colloidal activity index it is not sufficient for the reduction of the swelling pressure to negligible values. Because it was not possible to determine the initial water content of the marlstone directly, core samples were extracted from behind the cut slope from depth corresponding to the layers underneath the highway. The samples were tested for swelling after lime addition up to 3%. The results were used in the same manner as for soil without binder (as mentioned in previous sections) to develop equations describing the swelling after lime addition.

- Predicted value of the swelling pressure is given by the equation:

$$\sigma_{swel,ca} = \left( V_{ca} \cdot I_p \cdot I_c \cdot I_a^{0.2} \right) \cdot \left( 2.38 \cdot \ln \left( \left( \frac{1}{V_{ca}^{0.8}} \right) \cdot I_p \cdot I_c^{1.2} \cdot I_a^{0.2} \right) - 5.59 \right) [\text{kPa}] \quad (4)$$



where:  $I_p$  - plasticity index [%],  $I_c$  - consistency index [-],  $I_a$  - colloidal activity index [-] and  $V_{ca}$  - volume of lime added [%].

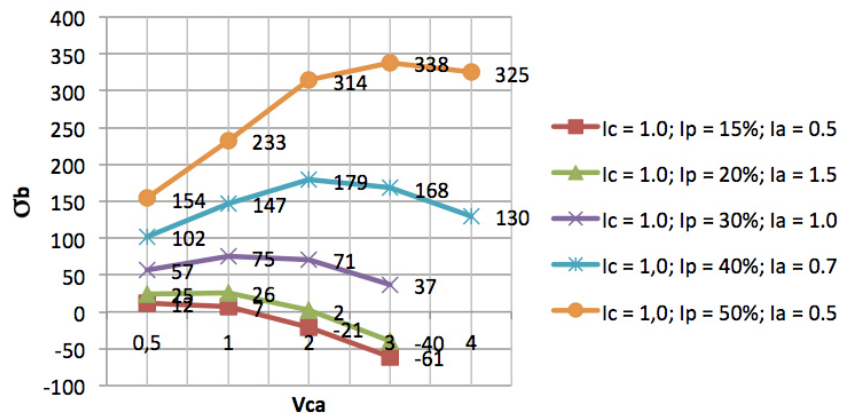
Note: the equation is valid for added lime volume  $V_{ca} \geq 0.5$  %.

- Predicted time of swelling for soil with added lime

$$T = 0.00134 \cdot \left[ V_{CB}^5 \cdot H_v \cdot I_p^3 \cdot 1.79 \cdot e^{\left( \frac{-8.12 \cdot V_{ca}^{0.5}}{I_c^{0.3}} \right)} \right] \text{ [months]} \quad (5)$$

where:  $I_p$  - plasticity index [%],  $I_c$  - consistency index [-],  $I_a$  - colloidal activity index [-] and  $V_{ca}$  - volume of lime added [%].

The graph in Figure 1 shows the development of swelling pressure after lime addition in a soil of given parameters. Where the value is negative, the soil is no longer swelling. For initial consistency index  $I_c = 1.0$  and swelling layer with lime thickness  $H_v = 50$  cm, the swelling time is apparent in the graph in Figure 2.



**Figure 1.** Swelling pressure  $\sigma_b$  development for different volume of lime added  $V_{ca}$ .

It is clear that the time of swelling of the soil with lime is proportional to the swelling pressure, as shown in Figure 1. If the soil has high plasticity index, then even after lime addition the swelling pressure remains very significant even though the reduction from the original soil is distinctive.

In order to prevent swelling of the modified material puzzolanic reaction must take place. Its initiation has one condition in the case of lime, the LMO (lime modification optimum). It is a state when the pH reaches 12.45 at a temperature around 25°C. In case this condition is not reached, exothermic reaction (drying of the soil) and flocculation (clustering of clay and silt particles into silt and sand particles) takes place. This happens quite quickly (hours to days) but gives only better physical and mechanical properties of the soil and better workability. At this state the porosity and permeability increases, but it has virtually no influence on the swelling, on the contrary, if future water donation should take place, the swelling conditions would be even better resulting from initial water content. It is known that loosely related to the mineralogy of the soil, the LMO is reached at 3% of added lime, for more active minerals of the Ca group (particularly Na montmorillonite) even higher. We know that usual volume of added lime is lower than 3% which is enough to improve physical and mechanical properties of the soil and its workability but not enough to start the puzzolanic reaction leading to soil strengthening and higher resistance to swelling. In the case sufficient volume of the lime was added and the LMO was reached, the water environment is needed. This is the first complication – if we add too much lime, the material is disrupted and the water environment ceases to exist. If all conditions are favourable, exothermic reaction and flocculation follow, then the lime



(CaO) is turned into calcium hydroxide  $\text{Ca(OH)}_2$ . The high concentration of OH ions in alkaline environment starts at low temperature to transform Ca, Na and K ions into solution (more similar to gel) and starts to break the  $\text{SiO}_2$  bonds in silicates and aluminates. New needle-shaped minerals grow through the soil structure from the gel, thus strengthening the soil. This is very slow process, according to literature the first signs can be observed after 28 days and full development can be expected after 90 or more days. The process causes decrease in porosity and permeability, the soil strengthens and therefore increases its resistance to swelling. Attention has to be paid to the formation of ettringite which is swelling itself! It was described that for the lime the process is quite complicated and time-demanding, therefore it is suitable to use mixed binders with the ratio 1:1 or with major portion of cement.

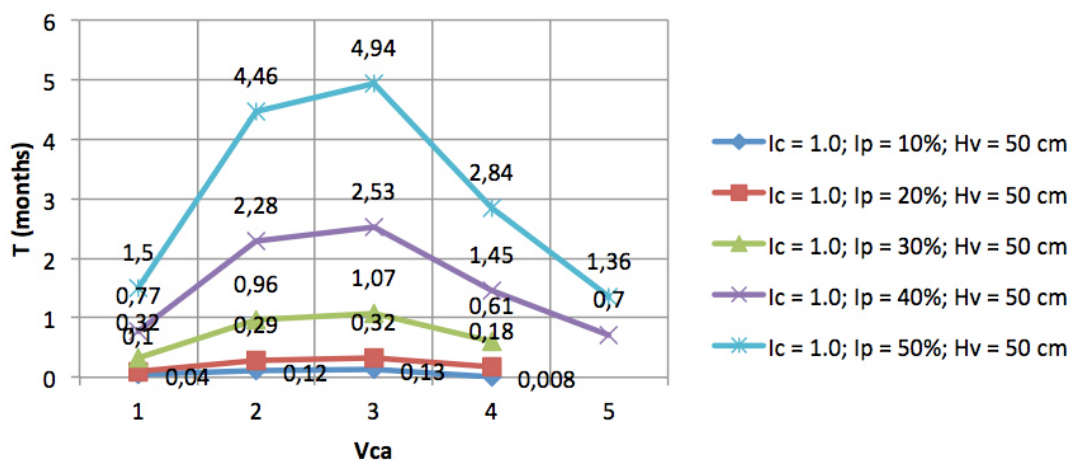


Figure 2. Swelling time T in months for different volume added lime  $V_{ca}$ .

#### 4. Impact of swelling

Swelling can be divided on the free and pressure (or resistance). The free swelling is typical for cut slopes where the volume change can be without influence of the structures. In the case of pressure swelling the upper structure (e.g. concrete pavement) acts against the swelling pressure on the soil till reach the state of equilibrium. Generally, the swelling will be stopped in the case of the balanced moisture. The deformation in the free swelling can be four time higher than in the pressure swelling. The value of the swelling pressure can reach 3600 kPa at clays with plasticity index above 80% and low initial moisture. So high pressures can have the significant destruction effects for upper structures or tunnel linings. The swelling has also impact on the soil parameters.

##### 4.1. Damage of the highway

This subsection shows the impact of swelling on the rigid slab of D11 highway in the Czech Republic. Section of the D11 motorway in km 76,000 was opened into use in December 2006. There were discovered instability of slopes on both sides of the highway and cracks in the concrete surface. Figure 3 shows the damage of the rigid highway pavement made of Portland cement concrete and Figure 4. is view on the circa 20 mm vertical shift of the slabs (the slabs have been grinded off). The kinetics of swelling was seen relatively quickly [6].



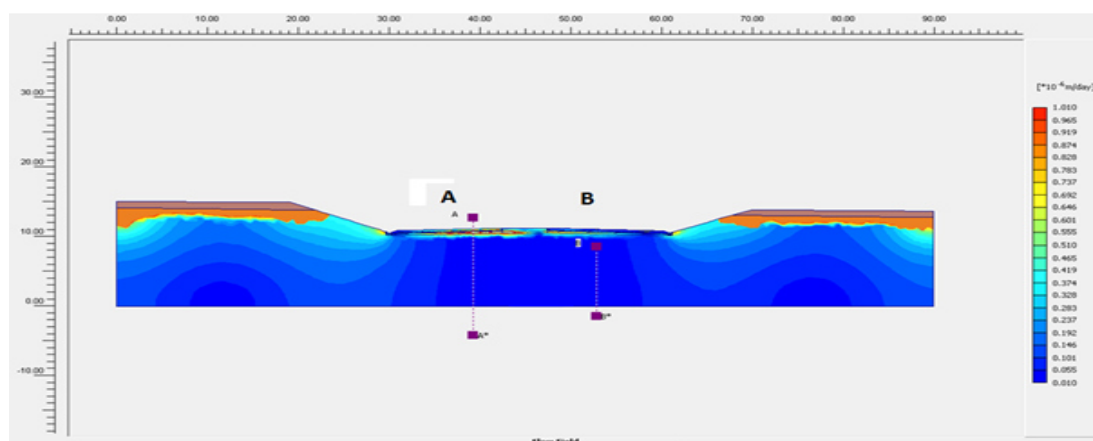


**Figure 3.** Disruption of the concrete road structure due to soil swelling, the direction of Prague.



**Figure 4.** Detail of cracks in the left lane at the 76,000 km in summer 2010. grinded off.

The concrete slabs had to be repeatedly grind due to fault of the surface was several centimeters. The shift of two slabs reached several centimeters and the surface had to be grinded off several times. The slab thickness after construction was 24 cm. After the grinding the shift reached up to 8 cm and the recommended speed was of 80 km/h, instead of the projected speed of 130 km/h. The numerical modelling of the water flow in the subsoil was carried out at CTU in Prague, FCE (Department of geotechnics) using Plaxis software. The FEM model showed that the deep drains at the bottom of the undercut slopes massively saturated road subsoil, even from the middle lane divider (Figure 5). Underlying marls, although very little permeable, has very high capillarity. Well, it results in saturation of the subsoil and intense swelling of subsoil under the road with a totally destructive impacts.



**Figure 5.** Numerical model of the water flow in the subsoil.

The standards or criteria often requirement only the values of the linear swelling but they tell nothing about the swelling pressures. And the swelling pressures have destructive effects. Deformations are only an accompanying phenomenon. Table 2 shows swelling pressures at relative deformation 3% for different soils. As it is obvious for the various initial parameters of different swelling pressure the deformation is still 3%. Based on this fact, the authors developed classification of cracks development on the road surface (indicative only). The classification is shown in Table 3.



**Table 3.** Classification of cracks development on the road surface.

Swelling pressure	Evaluation	Asphalt surface	Concrete surface
< 30 kPa	Negligible	De facto no	Virtually impossible
30 – 60 kPa	Increased	little noticeable surface deformation -	They may see the first signs of cracks
60 – 100 kPa	High	Slight undulations	Clearly visible cracks on surface
> 100 kPa	Very high	Significant undulations, depending on swelling pressure	Significant cracks and slip of the broken slabs

As seen from Table 3 the deformation on the surface are visible in the range of 30 to 60 kPa of swelling pressure in the subsoil. Contact stress below the structural layer of road with thickness 65-67 cm (on the subgrade) is about 14 to 16 kPa. If we consider the unit weight of the structural layers and the concrete surface  $23 \text{ kN/m}^3 * 0.7 \text{ m}$ , we have about 16 kPa. Not every sublayer has unit weight  $23 \text{ kN/m}^3$ , some materials have a lower unit weight. If the swelling pressure is 200 kPa or more, then it is obvious the final result. Swelling pressures were greater than 300 kPa on the described part of motorway D11.

## 5. Conclusion

In this paper, the dependence of the swelling pressure of expansive soils in the Czech and Slovak Republic on the soil properties was examined. Based on the multiple regression analyses made on the extensive experimental activities the reliable correlations have been established for swelling pressure, swelling strain and swelling time with initial water content, initial dry density, plasticity index, consistency index and colloidal activity index. Compare of the measured and predicted swelling pressure values indicates a high prediction performance (the correlations coefficient  $R^2 = 0,88$ ). For the soil modification by lime it was not possible to determine the initial water content of the marlstone directly, so the developed equations describing the swelling after lime addition were presented. The authors believe the presented relations are a suitable alternative for the classical calculations and give quick prediction of swell pressures from easily determined soil properties. There are described the problem with soil swelling on the highway D11 in the second part. The authors also show classification of cracks development on the road surface based on their current knowledge of the problems.

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