Friendly environment solution for a suffusion case

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Abstract. The paper describes about solving the phenomenon of suffusion in the foundation ground of a building. The soil was investigated with direct and indirect methods (drilling and dynamic penetration, electric tomography, seismic refraction). The filling of the cavity was made with a low permeability or practically impermeable material, homogeneous in granularity, with approximately the same stiffness as the surrounding soil.

1. Introduction
Suffusion phenomena represent a major risk for engineering construction. The frequency with which they affect the constructions is relatively low compared to other geotechnical risks (earthquakes, landslides etc.). If the phenomenon of suffusion in artificial dikes is not taken into account, where they represent the main danger, the appearance of suffusion crater occurs mainly in the urban center causing emotions. According to the publication, they are more common, which indicates that the causes of the triggering are mostly anthropogenic [1]. Probably for this reason these phenomena are not explicitly included in the hazard area studies. Consequently, addressing the phenomenon, both in terms of causes and effects, and in terms of solutions, is not systematized in literature, and the resolutions of different situations have an artisanal aspect. This article presents an extreme situation caused by such a phenomenon and describes the stages of investigating causes, uncertainties and feasible solutions.

2. About the suffuses phenomenon
Originally suffusion means when something slowly spreads throughout something else. With some different nuances in the soil case, there are several ways in which this phenomenon can manifest and as a result it can be described under different names according to the mode of manifestation, figure 1.

Internal erosion:
- Concentrate flow
- Regressive erosion
- Contact erosion
- Suffusion

However, they all share some common elements:
- Migration occurs under the action of a hydrodynamic current
- The migrating material leaves voids behind; those voids are moving in the opposite direction to the migrant material.

In the case of the last two forms of void migration (contact erosion and suffusion) there are at least two different entities, by granularity in the case of soils: the first one is migrating inside of the second. Voids genesis is conditioned by three factors:
- The existence of a nucleus of voids, which usually has a different cause than the occurrence of the phenomenon of suffusion;
- Spatial ratio between the two components;
- The ratio of the current force to the granularity of the migrant component.

**Figure 1.** Different types of internal erosion or suffusion [2].

For the case of internal erosion and concentrated flow, the current force of water must be determined by overcoming the critical hydraulic gradient.

In case of the suffusion, the hydraulic gradient must not necessarily reach the value of a critical hydraulic gradient calculated for the whole soil’s layers.

Its value must be able to train only the smallest particles provided that there is a gap in the continuity of the particle size curve.

This particle gauge, namely the gap correspondent, will represent the free space through which the fine particles will circulate.

In other words, the cumulative curve must have a horizontal plane, which would indicate the existence of the corresponding gaps, whereby it is possible to migrate the fine particles among the coarse particles.

Several formulas are known in the literature to indicate a limit. Granulometry criterion for the phenomenon so called “Grain Size Criteria”; the limit state equation can be written in the following general form [3]:

\[ Z = f(Cu) \ \text{d}_{85,F} - \text{d}_{15,S} \]  \hspace{1cm} (1)

where \( \text{d}_{85,F} \) is a diameter such that 85% of the grain’s diameter of the filling are smaller than this size, \( \text{d}_{15,S} \) is a diameter such that 15% of the grain’s diameter of the skeleton are smaller than this size, \( f(Cu) \) is function of uniformity coefficient.

The positive value of \( Z \) gives the stage of the safety of this simple system. Another example is the Terzaghi criterion (Terzaghi and Peck, 1948) with \( f(Cu) = \text{const.} = 4 - 5 \), including some factor of safety and \( C(cu) = 9 \), which is only valid for uniform material and filter combinations:

\[ Z = 9 \ \text{d}_{85,F} \ \text{d}_{15,S} \]  \hspace{1cm} (2)

Or another criterion for recognizing land that presents a danger of suffocation is given by the relationship (A.N. Patrașev, Gh Pradevnîi, 1963 – [4]):
\[ \alpha = \frac{d_3}{d_7} \geq (0.32 + 0.16 \cdot \frac{d_{40}}{d_{10}}) \cdot \sqrt{\frac{d_{40}}{d_{10}}} \cdot \frac{n}{1-n} \]  

where \(d_3, d_7\) have the same meaning as described above.

In addition to the granulometry criterion, an additional element may emerge in the formation of the funnels suffuses to trigger the activation of the phenomenon, namely the collapse of the roof of the initial void under its own weight.

The conditions in which these situations arise are studied in detail in particular in the case of underground excavations, mine galleries, tunnels etc.

3. Geological situations where naturally occurring phenomena of suffuses may occur

In the whole literature, the existence of these naturally occurring creeks is related to a limestone base in which some karstic voids occur at some point, and the above layer, usually limestone, fall into this void under its own weight (figure 2).

Rather, the phenomenon is mentioned in connection with loessoid, macroporous formations, but this hypothesis should not be considered in the studied area.

![Figure 2](image.png)

**Figure 2.** Evolution of suffuses cone in the case of a fine (a) or coarse (b) layer over limestone [5].

Once the deep gap is formed, it is possible for the fine particles in the roof to be trapped by a descending stream of water, and the gap to migrate in reverse direction to this current in a regressive way.

Another hypothesis, less probable but possible in the case studied, is that of an internal regression erosion, namely: precipitation infiltration waters accumulate at the base of the alteration bark and form a current between the base rock and the prologue deposits capable of trains and fine particles.

In urban areas, the phenomenon was manifested mainly by defective municipal networks (sewers, water supply pipes).

In this respect, there are spectacular examples of enormous sinkholes in cities, with depths of hundreds of meters sometimes and with diameters of meters or tens of meters.

4. History of the emergence and specific development of the cavity in Brasov

The studied area comprises an area in a residential district at the base of the south-eastern slope of Tampa Mountain, in the city of Brasov (figure 3).

On the land there are several blocks of flats which have a height regime D + P + 2, P + 3E or D + P + 4E. The constructions were put into use in the years 1982-1985 and so far they have generally behaved well (figure 4).
Figure 3. Geological map of the area (scale 1:50000, according to 1972 Geological Institute of Romania).

Figure 4. Situation plan.
The exception made the foundation ground of the block; so in the summer of 2017 the tenants observed the existence of a cavern of 4x4x4.5 m under the foundation on the downstream facade of the block. On the southern side of the block appeared in a cavern with a depth of approx. 4.20 m to the surface (figure 5).

![Figure 5. Profiles with the affected block resulting from the scan; the foundations and the position of the cavity are highlighted.](image)

It was shaped like a flat-bottomed pear with a diameter of approx. 4 m and a depth of 4.20 m below the block foundation. The lateral walls of the cavern were circular in shape, and they were smooth, wallowed with concentric layers, probably due to the precipitation of some salts (figure 6).

![Figure 6. Cave Pictures in December 2017: (a) the northern wall of the cavern, under the block; (b) the “floor” of the cavern is about 50 cm higher than in September; (c) the western wall of the cavern.](image)

Later, the cavern reduced its size by about 50% lower due to the slowness of the material on the southern, downstream wall. The sidewalks in the North-East corner are left with a maximum of (7-10) cm, relative to the thermal insulation that was executed 3-4 years ago.

4.1. Considerations on geological-geomorphological context from the point of view of the suffusion
The studied site belongs geomorphological to the piedmont on the southern slope of Tampa Mountain.
Piedmont was formed by the junction of some manure cones, resulting from the deposition of the disaggregated material and transported by the torrents.

As a result these proluvian deposits have a cross-stratification in which alternate layers with very varied granularity (boulders, clays, sandy gravel sands). Over them lay a deluvial clay layer, which flows downstream.

The bedrock, meaning a Tithonian-Barremian age limestone of Jurassic lies at much greater depths of tens, perhaps over a hundred meters (figure 7).

The Jurassic reef limestone forming the Tampa Mountain allows the development of such karst voids. On Tampa there are at least two entrances in a karst system, near the Tampa Saddle, at a much higher altitude than the investigated area, with approx. 200 m. The system was not explored, but from the accounts of those who entered the first portion and stopped at the mouth of some vertical wells, they seem to have a size of at least the order of tens of meters. An additional argument is the existence of the cave on the Rasnoavei Valley, developed in the same type of limestone, which is very large in the order of hundreds of meters long, with impressive halls, true cathedrals inside. Investigations to determine the causes and magnitude of the phenomenon. Some images from the cavity investigation are presented in figure 8 and the geoelectric profile in figure 9.

![Figure 7. Geological profile through Valea Cetatii (extended karstic system is hypothetically; until now in real way it has been investigated only few meters on the top of the mountain).](image)

![Figure 8. Images during cavity investigation.](image)
Figure 9. Geoelectric profile parallel to the building facade. Red areas indicate high electrical resistivity; the position of the cavity is observed at one third of the length to the right.

For deciphering the conditions in which the phenomenon occurred, they were made:
- 4 continuous drilling,
- 10 reconnaissance drills,
- two open ditches;
- three electrical tomography profiles;
- 3 Lefranc tests to determine permeability in situ;
- 5 samples from the cavern were harvested,
- the cavern was scanned,
- sewer networks in the area were video investigated.

5. Comments on the results of the investigations
In principle, in the upstream area, a clayey cohesive complex has been found to surface up to approx. 10 m after which all the drillings (except F 1 that stopped above) penetrated into a coarse material made of gravel or limestone blocks and submerged rounded conglomerate in a sandy matrix. It cannot be said that the bedrock has been reached. The soil permeability coefficient determined by the Lefranc method was: in the F1 drilling depth of 10 m (in slurry clay) \( K = 5.05 \times 10^{-5} \text{ cm/sec} \). in F2 drilling with 3.55 m deep (in slurry clay) \( K = 6.2 \times 10^{-6} \text{ cm/sec} \). In the F3 drilling depth 10.0 m (in clayey matrix groove) \( K = 7.82 \times 10^{-6} \text{ cm/sec} \). Geophysical investigations, meaning electric tomography, have highlighted areas with low resistivity that could indicate the existence of other drought gaps, or the “channel” through which the water with the washed material protrudes into a collector. Reconnaissance drills made after the electrical tomography (about 10 in number) did not confirm the existence of any void. Low electrical resistance areas have been found to be coarser soil.

Figure 10. Imperfect sewer connections on the CM4-CM3 sewer; the roots penetration and aggregates deposited on the tube (the images are rotated differently).
Figure 11. Images from the video inspection of the drain under the block; aggregate deposits are deposited on about half of the drainage section and precipitation of salts on the walls (the images are rotated 90° in a trigonometric sense).

The video investigation of the sewerage networks led to the following observations: The drain that crosses the building is half filled with washed soil (figure 10 and 11).

When it was filled with water (about 3 cubic meters), most of the volume followed its normal course, reaching the opposite dormitory, the eastern one, then the downstream sanitation (about 30 seconds). However, some of the water crossed the foundations of the block, and rolled over the basement floor to the room above the cavity. Moreover, this room has the floor left 30-40 cm halfway out of the block.

As can be seen in figure 12 there are satisfied from the granulometry point of view of the conditions mentioned in the literature. Thus, the granularity of the silty-clay matrix of gravel, where over 70% of the coarse material (sand and gravel) and 19.27% (colloidal) clay are observed, compared with only 9.4% of silt, which represents the “gap” mentioned above.

Figure 12. Example of a granulometry test performed on the claystone matrix.
Granulometry analyzes carried out on the harvested samples show that this criterion is fulfilled both for the red clayey complex of deluvial genesis and for the proluvial deposits. Another argument is the existence of the aggregates (of the earth) in the sewer pipes, which can represent the material in the cavern.

The amount of aggregate in the tube is not very significant as long as it can be reduced by washing. The joints between the sewer pipes are faulty. They see almost every joint as the roots of the plant penetrated through the joints.

The networks are made of concrete tubes in a one-meter section, which, besides the problems of execution, seem to have been involved in the motion of the earth, enough to create significant joints for the process of suffuses.

6. Solutions adopted and verifying their sustainability

As a result of the emergency work, the block was secured by improving the adjacent ground by means of injection of material (bentonite solution, cement, sodium silicate) and cavity filling.

The safety of the block followed the following steps:

- Cavity filling;
- Obtaining the drain and injecting waterproof material into the drain;
- Creating a sealing veil downstream of the block;
- Execution of drainage works upstream of the block and rehabilitation of the sewage system;
- Exterior landscaping around the block.

The filling of the cavity was made with a low permeability or practically impermeable material, homogeneous in granulometry, with approximately the same rigidity as the surrounding soil.

A cork on the surface was created to fill the cavity and then injected with downstream material at a reduced pressure (maximum two atm). After approximately filling the filling cavity, injecting material from the basement, the drain was blocked at both ends with concrete plugs after which a suspension of bentonite was injected with 2-3 atm. pressure. Pressure limitation is required to avoid penetration of the subsoil with injections.

A sealing veil was formed from a series of grouting injections (bentonite and clay) at a distance of one meter to a minimum depth of 9 m. The arrangement of the injection line is parallel to the block at a distance of 2 m from the facade.

Parallel to the upstream facade, at a distance of one meter, a drain with a minimum depth of 2.5 m will be executed.

The drain behind the supporting wall near the pavement of the street, including the barbacans, will be restored.

The sewer network has been redesigned so that the rainwater will be removed from the block and the joints will be secure.

During the execution, we found the following:

- Large suspension losses in some injectors I4 (4454 l), I5 (4651I), I6 (4192 l) and I7;
- at injector I7 between 7-12 m depth – total suspension loss (zero pressure bar pressure); the injection was resumed for 5 consecutive days, and an injection pressure of 4 bar was achieved after a total consumption of 4847 l of suspension (1/3 C/A);
- Two dynamic heavy penetrations were made up to 16 m deep, resulting that the soil is loose, poorly consolidated, with gaps made by washing / moving fine particles.

The work has been visually controlled and verified by laboratory tests and “in situ” tests (dynamic penetration) and it has been ascertained that the required requirements have been met.

The material was inserted into the cavern in elementary thicknesses of 25 cm thick, from the surface downwards.

At least two oblique tubes were mounted from the surface to the bottom of the cavern. After hardening of the material cast in the cavern, a new amount of 3 atm. to 5 atm. was injected at 2-7 days until refusal.
7. Conclusions

The investigations carried out have not intercepted other caverns or churning funnels. Besides, it would have been very unlikely that such a supposed goal would hit a survey. However, the results indicate that there are obvious prerequisites for their existence, especially in terms of dynamic penetration.

Figure 13 shows the number of blows (penetration resistance) v depth. It can be noticed that after the surface filling layer, resulting from landscaping and general excavation between depths of approx. 3-6 m was encountered a layer of coarse deluvial clay with a relatively high resistance to dynamic penetration. It is then observed a decrease in penetration resistance, because at a depth of 15-16 m there is a minimum (2-4 strokes/10 cm). Normally in a uniform stratification, unaffected by other factors, the penetration resistance increases with the depth on the one hand due to the consolidation of the lower layers under the load of the top of the earth column and on the other hand due to the rotation of the rods, which is particularly significant in the case of the clays. A statistical processing of these penetrations indicates at a depth of 13-16 m a pore index of 0.8-1.25, which is very much for a normally consolidated ground.

![Figure 13. Dynamic penetration resistance charts performed by Geosond S.A. (no. of strokes vs. depth).](image)

The study of the old topographical plans, which formed the basis of the urban plans on which the district was built, drew attention to the existence of a number of 44 funnels, assumed by existing suffuses, at the base of the southern slope of Tampa, between the slopes and the valley axis. We believe that their appearance is a natural and not anthropic phenomenon.

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