Suffosion hazard: Today's and tomorrow's problem for cities

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Abstract: Suffosion is a geological hazard caused by groundwater flow. Suffosional failures (leaching, piping, underground erosion) of soils or rocks, cemented by soluble material, are well known throughout the world. The process results in a range of phenomena: weakened zones, caves and voids, subsidence hollows, collapse sinks, swallow holes, landslides and sand volcanoes. In extreme cases buildings and structures may by threatened. The catastrophic destruction in 1983 of a five-storey dwelling in Kurgan city may have been caused by suffosional processes. In this instance, the rupture of a water pipeline may have triggered the collapse, which resulted in the death of 14 persons. Although, damage to property in urban areas arising from suffosion is usually not life-threatening, an estimated 958 Russian cities and towns are thought to be affected by this process, leading to an annual repair bill estimated at about £200 million pounds. Hazardous and damaging suffosion is predominantly a man-made phenomenon, caused by development activities that fail to take proper account of the geological environment. The engineering response is likely to see an increase in the use of anti-suffosion protection measures in years to come. This paper presents case studies based on Russian experience of engineering site investigation in urban areas. The problems of forecasting suffosion, based on physical and mathematical modeling, are discussed together with the use of protection measures.

Résumé: La suffosion est un processus géologique dangereux résulté d'écoulement de l'eau souterraine. Les effets de suffosion (lessivage, renard, érosion souterraine) sont bien connus dans le monde comme les ruptures d'un sol ou de la roche composée des debris cémentés par la matière dissoluble. Finalement les manifestations de suffosion suivants ont formées: zones désolides, cavitées, affaissements, effondrements, avaloires, glissements de talus, pseudovolcans. Aux situations critiques il arrive qu'un bâtiment ou une construction courtent un danger à la suite de leur contact avec une manifestation de suffosion. Les excès de suffosion sont les événements immanents dans les territoires urbains y compris des villes de Russie. La destruction en 1984 de la maison à cinq étages dans la ville de Kourgan est un exemple de tel accident. Il a été provoqué par une cassure de la conduite d'eau et a mené à la mort des 14 personnes. Cependant le dommage principal matériel résulté de la suffosion dans les territoires urbains est déterminé des accidents non-catastrophiques. Ce dommage sommaire annuel est à peu près 300 millions dans 958 villes de Russie. La suffosion détrimentable est pour l'essentiel un effet d'activité technique, parce que ce processus est très sensible pour les changements artificiels des élements géologiques d'environnement. Pour cett raison la croissance inévitable d'urbanisation transforme la protection contre-suffosion de problème du bâtiment d'aujourd'hui à problème de demaine. Ce rapport caractéris la suffosion au point de vue de géologie de l'ingénieur en considération d'expérience de Russie au domain de l'investigation de site dans les territoires urbains. Le problème de prévision de suffosion sur le base des modèles physiquees et mathematiques est analysé tant que la protection contre-suffosion.

Keywords: site investigation, geological hazard, failures, case studies, models, protection.

INTRODUCTION

The term "suffosion" is Russian in origin and was introduced by Pavlov (1898) to describe the process of removal and transport of small soil particles through pores. In more recent usage (Khomenko 2003), the term has been broadened to include the failure that occurs in rocks and soils when particles are removed by subsurface water flow – a process well documented in karst terrain. The leaching, piping, and underground erosion that result from suffosion give rise to a wide range of landforms including caves, subsidence hollows, collapse sinks, swallow holes, landslides and sand volcanoes.

SUFFOSION IN CITIES AND TOWNS

Man-induced suffosion is extremely widespread in cities and towns, where it is usually related to construction work, leakages in water pipes or changes in the groundwater regime caused by pumping. Other dependent factors are the population density, the height of the buildings, and the number of industrial and infrastructure units.

Surprisingly, the effects of suffosion are not restricted to modern cities, but can also be seen in older historic sites. In Russia and Ukraine, deformation of historic buildings and architectural monuments can usually be attributed to one or more of the following:

- A thick suffosion-prone cultural layer (made ground)
- The presence of defensive earth embankments and structures
- Preferential location in areas of contrasting relief (high hills, steep banks of rivers, lakes, gullies etc.)
- Artificial caves (underground passages, cellars, wells), including those abandoned and unrecorded

- Voids formed by the destruction of wooden piles once widely used in building practices in many regions of the Russian state

DAMAGE CAUSED BY SUFFOSION IN URBAN AREAS

It is commonly accepted that the most hazardous suffosion effects are those that relate to water-engineering structures. However, this is not necessarily so. Case studies show that the 1983 failure of a five-storey block of flats in the town of Kurgan (Russia) caused the same number of fatalities as the 1976 destruction of the earth dam Titon in the state of Idaho. Both failures involved suffusion but in the Kurgan flat collapse, a damaged water main was all that was required to trigger the landslide that caused the fatalities.

In another example, dating from 1986, more than 50 houses and a dog-care centre were destroyed in a suburb of Brasilia by a massive collapse caused by underground erosion. Here the problem was exacerbated by the presence of deep cesspools near every house (Mendonça, Pires & Barros 1993). In the eastern states of the USA, suffosion is linked to karst development and is accompanied by widespread collapse and damage to property. As recently as 1980, the destruction of a warehouse in the town of Rossville, Georgia represented a loss of $1.4 million (Newton & Tanner 1987). In the 1970s, more than a hundred buildings in one district of the town of Yerevan (Armenia) were damaged, many beyond repair, as a result of chemical suffosion (leaching).

Although major incidents of the type noted above are reported from time to time, most damage caused by suffosion does not result in major accidents and catastrophic failures but occurs on a small-scale, is a result of continuous or periodic activity, and often causes barely noticeable adverse effects. However, one estimate (Ragozin 1993) suggests that damage of this type can be observed in 958 towns and cities across Russia, with an approximate annual average economic cost to the nation of half a million roubles (about • 200 million at 1990 prices).

Paradoxically, protective measures put in place to resolve engineering problems can themselves trigger suffusion-related failures. Coastal defence works and damaged anti-landslide drainage galleries are just two examples where suffosional phenomena have been noted. Collapse of loess soil that has become saturated is also well documented.

Figure 1. Destruction of building caused by suffosional collapse sink formation in Moscow in 1998

RECENT EXAMPLES OF HAZARDOUS SUFFOSION PHENOMENA IN RUSSIA

Case study 1

In May 1998 a suffosional collapse sink formed in Bolshaya Dmitrovka Street in Moscow. The collapse sink brought about the destruction of a two-storey building (Figure 1), which, luckily, was empty at the time. The collapse occurred because saturated sand broke into a deep underground interceptor tunnel, which was being excavated (Figure 2). According to newspaper and TV coverage of the event, as the water and the quicksand broke into the tunnel, the collapse sink diameter grew from “small” to “quite significant” in a few minutes, however, its margins did not extend to the adjoining buildings.

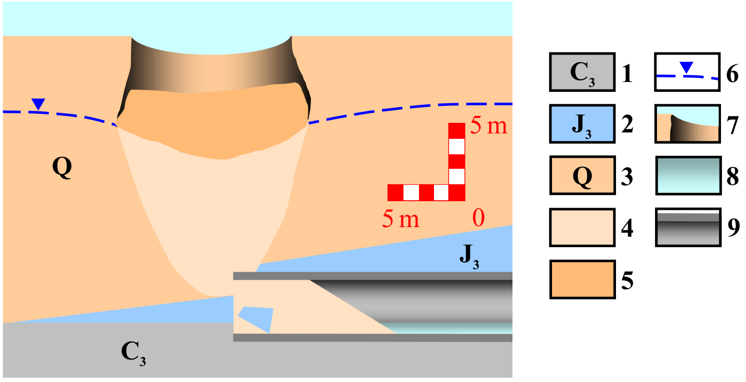


Figure 2. Schematic cross-section through the collapse sink (Figure 1)
1. Carboniferous limestone. 2. Jurassic clay. 3. Quaternary sand. 4. Saturated sand (quicksand) dislocated by piping.
5. Collapsed non-saturated sand. 6. Ground water level. 7. Collapse sink. 8. Water. 9. Tunnel

The author of this paper carried out a geological analysis of the site and also modelled the failure event mathematically from observations taken at the time. It appeared that during the first stage of the collapse the diameter of the sink increased in accordance with the model predictions (Figure 3a,b).

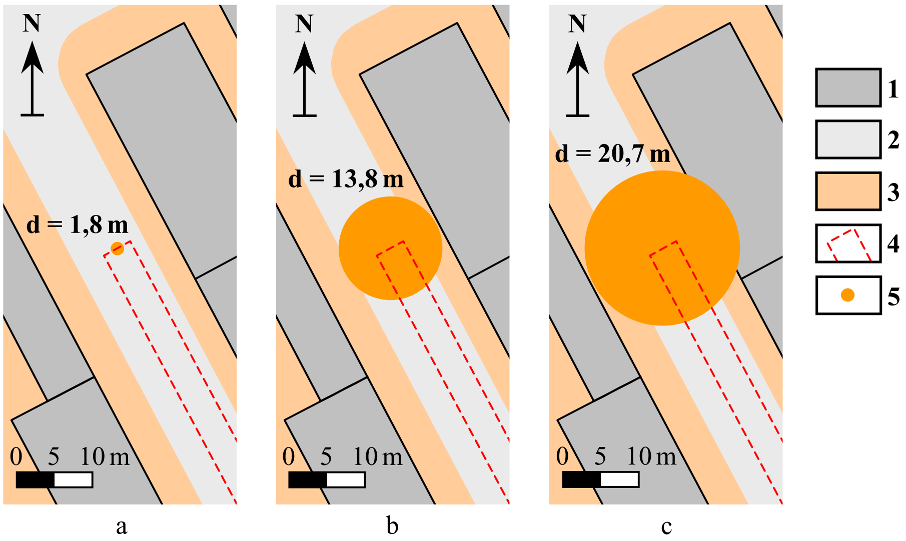


Figure 3. Model reconstruction of stages in the catastrophic development of a collapse sink, Moscow, 1998 (Figure 1) caused by man-induced suffosion. (a) Initial stage of collapse (b) Final stage of collapse (c) Failure of sloping collapse sink walls
1. Buildings. 2. Highway. 3. Foot-path. 4. Tunnel. 5. Collapse sink (d – forecasted diameter)

The statement by one witness that the collapse sink looked like “a bottomless abyss” supported the conclusion that in the initial collapse not only did the whole mass of saturated sand affected by piping flow into the tunnel, but the overlying mass of non-saturated soil also failed. The quicksand flowed back along the tunnel as far as the nearest shaft 130 m from the tunnel face. In the final stages of failure, a rapid increase in the diameter of the upper part of the sink occurred as discharge of groundwater through the walls of the sink, combined with surface run-off and infiltration from a damaged pipe brought about further failure of the sloping walls. Repair works required more than 1,000 m^3 of earth to fill the collapse sink.

Figure 4. Deformation of house caused by suffosion subsidence in Shchyolkovo, the Moscow region, in 2002

Case study 2

In 2002, the appearance of damaging cracks in a five-storey block of flats in Shchyolkovo, in the Moscow region (Figure 4), prompted further investigation. The results of an engineering site study showed that the damage may have originated as a result of mechanical suffosion beneath the northwestern part of the building (Figure 5). It was suggested that infiltration of surface water through the adjoining lawns coupled with leakages from nearby sewage and heating conduits initiated the process.

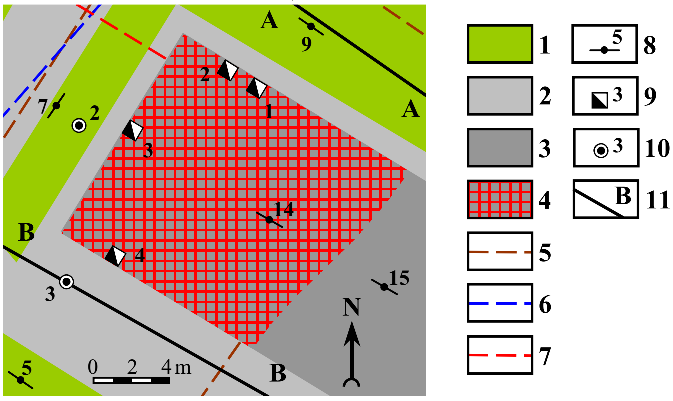


Figure 5. Northwestern part of the site of house damaged by suffosion in Shchyolkovo (Figure 4)
1. Lawn. 2. Asphalted surface. 3. House. 4. Zone of deformation. 5. Covered sewage conduit. 6. Covered water conduit. 7. Covered heat conduit. 8. Point of geophysical vertical electrical sounding and its number. 9. Pit and its number. 10. Borehole and its number. 11. Cross-section line

The water would have flowed towards the central part of the building and then drained through hydraulic windows in the underlying Jurassic clay into swallow holes in the Carboniferous limestone, below (Figure 6). The gravitational flow across the steeply dipping (24 °) Jurassic clay would have been sufficient to flush material into the swallow holes, leading to eventual removal of support for the building.

Possible explanations as to why the deformation of the building only appeared in 2002 are as follows:

- Low but constant levels of leakage from the sewage conduit over an extended period of time would have been sufficient to cause suffusion and gradual removal of sand. However, only when a critical point was reached in 2002 when the bearing capacity of the sand was exceeded did failure occur.
- Another possibility is that infiltration to the site may have been controlled by natural climatic variations and by losses from seasonally operated heating systems. The response of the Jurassic clay to repeated wetting and drying would be to shatter and fissure due to its high shrink-swell susceptibility. Recurrent gravitational water flow across this weakened substrate would further concentrate the suffusion process.

It is likely that the failure mechanism involved elements of both processes. It may also be significant that the summer of 2002 was particularly dry throughout the Central regions of Russia, thereby creating optimum conditions for failure.

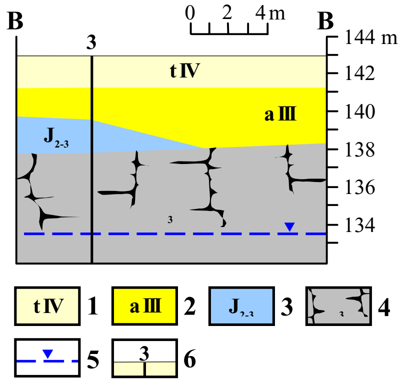


Figure 6. Cross-section through the line B-B (Figure 5)
1. Made ground. 2. Quaternary sand. 3. Jurassic clay. 4. Carbonic limestone with voids and fissures. 5. Ground water level. 6. Borehole and its number

FORECASTING SUFFOSION

Predictive methods used in other branches of engineering geology are equally applicable to suffosion forecasting. However physical modelling (model testing) is increasingly the preferred method for researching this process. Compared with other predictive methods used in engineering geodynamics it has the advantage of being able to examine not only the existing state of suffosion conditions but test more unusual situations which are a result of human activity. This is very important for simulating the types of conditions that arise in cities and towns. There are many designs of experimental equipment intended for laboratory model testing of suffosion. The equipment constructed by Khomenko *et al.* (1993) is particularly versatile (Figure 7).

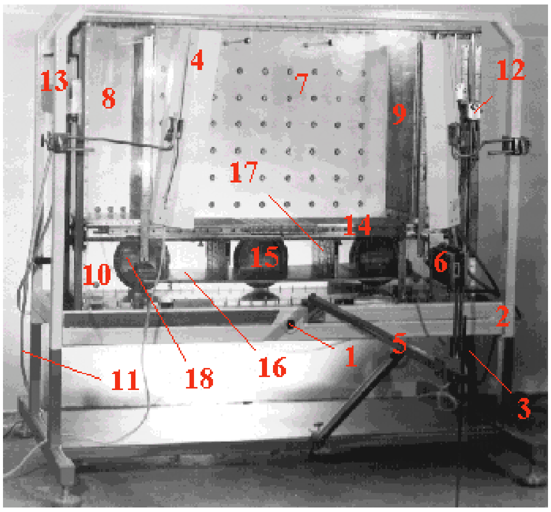


Figure 7. Equipment for modelling and forecasting suffosion
1. Axle. 2. Frame. 3. Sloping device. 4. Light. 5. Device for moving camera. 6. Camera. 7. Sample box with modelling material. 8. Side water tank. 9. Removing permeable wall. 10. Lower water tank. 11. Hose. 12. Device for water level variation in tanks. 13. Moving water tank. 14. Solid bottom of sample box transformed to perforated one with enlarging splits. 15. Enlarging box. 16. Moving bottom of enlarging box. 17. Moving and growing wall of enlarging box. 18. Cleaning hatch

A forecast makes it possible to give an estimate of a suffosional danger for the environment or engineering activities involving the economic activity. Such an estimate can be given only if the forecast allows identifying at least one out of the two criteria: suffosion appearance and a suffosion catastrophe (Figure 8).

The criterion of suffosion appearance (Figure 8a) expresses the boundary condition for the geosystem between the stable and the labile state or from one labile state to another, which corresponds to the beginning of certain phases or stages in the development of the suffosional process. In concrete circumstances the number of the suffosion appearance criteria established in the course of the forecast and their content depend on the character of the expected suffosional processes and on whether the forecast is at all possible. If it can be quantified, the boundary condition for suffosion appearance and its appropriate criterion (C_e) is expressed by the formula:

$$C_1 \geq C_e = f(C_2, C_3, \ldots, C_n)$$

where C is a numerically expressed condition for the suffosional process, and n is the number of such conditions.

The above formula expresses the boundary conditions sufficient for suffosion to appear with an increase in the value of C_1, representing in this case the initiating factor numerically expressed. If necessary, the left hand side of the formula can contain any of the values capable of changing and included in the function, with a possible change of the inequality sign. In other words, if the suffosional process can be caused by a change in another condition defining its course, this is easy to show by a translation of the formula, and in this case the suffosion appearance criterion will have a different physical sense.

When the boundary condition for suffosion appearance is met, it is highly probable for dangerous suffosional phenomena, which are really capable of harming the environment to appear. It is sometimes possible to apply only this criterion for estimation, especially in the early stages of designing non-existent objects, but as in the application of this criterion it is impossible to take into consideration the vulnerability of these objects, this being determined by many circumstances, the suffosional danger in such cases is usually overestimated.

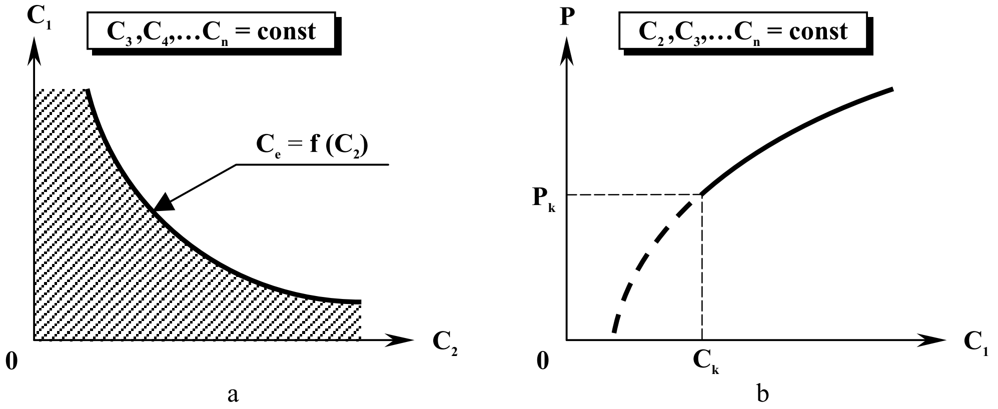


Figure 8. Typical boundary conditions of a suffosional danger determined by forecast. (a) The suffosion appearance: safe combination of numerically expressed conditions for the suffosional process (C_1 and C_2) is shown as shaded area. (b) The suffosional catastrophe: safe combination of numerically expressed condition for the suffosional process (C_1) and quantitative characteristic of the suffosional process or its manifestation (P) is shown as dash line

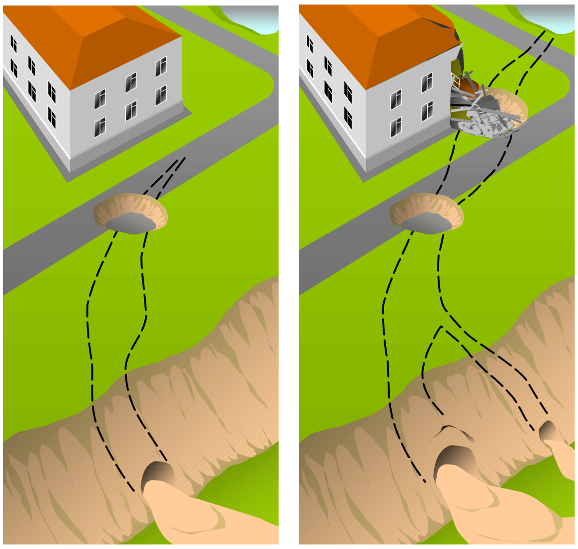
The estimation which takes into account the boundary conditions for a suffosional catastrophe is devoid of this disadvantage, but it requires, at the minimum, knowledge of the exact location, form and sizes in the plan of the designed or existing object. In an elementary case such estimation is carried out graphically by superimposing the contours of the objects which are hypothetically being destroyed on the forecast map of the suffosion development conditions and the parameters of the expected suffosional phenomena. Ideally, it requires comparison of the parameters characterizing the suffosional development in time with the terms of exploitation of the buildings and structures, and also the knowledge of their constructive and functional peculiarities. Only in this case is it possible to state unerringly that the suffosion development will lead (or, vice versa, will not lead) to social, economic or ecological damage. The analytical expression of the boundary condition and the criterion **(P_k)** of a suffosional catastrophe are expressed by the formula:

$$P_1 \geq P_k = f(C_2, C_3, ..., C_n)$$

where P is a quantitative characteristic of the suffosional process or its manifestation.

In certain circumstances it may be more convenient to use the form of the expression of the suffosional catastrophe criterion not through the quantitative characteristic of the suffosional process or its manifestation, but through a numerically expressed condition for the suffosional development (C_k):

$$C_1 \geq C_k = f(C_2, C_3, ..., C_n)$$



a b

Figure 9. Illustrative example of two-degrees catastrophe caused by the developing slope suffosion (underground erosion). (a) The initial situation corresponding to criterion of a suffosional catastrophe of first degree. (a) The final situation corresponding to criterion of a suffosional catastrophe of second degree

Several criteria of a suffosional catastrophe may be established for one and the same geosystem, which is usually accounted for by different vulnerability and importance of its components, as well as by different consequences of their destruction. This is mainly the case of natural-technogenic geosystems and their technogenic components. Let us consider an elementary situation when there is a motorway between a house and a suffosion-prone slope (Figure 9). Without doubt, two criteria of a suffosional catastrophe should be borne in mind: one criterion is characterized by the spread of the suffosional destruction zone onto the road (Figure 9a), the other – its spread under the house foundation (Figure 9b).

In a certain situation one of the suffosional catastrophe criteria may coincide with one of the suffosion appearance criteria. Imagine, for example, two housing estates located next to each other. One of them contains old wooden one-storey houses built on separate supports, the other is covered with modern many-storey blocks of flats with foundations made of monolithic reinforced concrete slabs which are not destroyed even if a six-meter diameter collapse sink is formed. In such a case, with a suffosional collapsing formation expected on this territory, the boundary condition for a suffosional catastrophe for the housing estate construction will be an excess of the six-meter value of the suffosional collapse sink diameter. Within the limits of the old housing estate the boundary condition for a suffosional catastrophe coincides with the boundary condition for the suffosional collapsing formation.

Obviously, in certain situations the estimation of the expected suffosional danger according to both of its criteria may be a complicated procedure during which it is necessary to draw and analyze a whole series of auxiliary maps. Their mutual composition results in the appearance of various scales with definite contents on the final map presenting the suffosional danger estimate for the given territory. For example, such a map will identify the areas scaled as "safe", "relatively dangerous", "quite dangerous", and so on for concrete natural and technogenic structures, kinds of construction and economic activity.

Table 1. Classification of anti-suffosion protection measures

Type of protection		**Protection technique**
Passive	Planning	Safe location of building or structure on the site and correct choice of design
	Constructional	Special foundations including pile ones. Special construction of buildings and structures
	Controlling	Monitoring of: suffosion-prone soils and rocks in contact with the structure especially within foundations; subsurface water; earth surface including slopes state; tensions and deformations in constructive elements
Active	Provoking	Making the subsurface water flow in suffosion-prone soils and rocks. Dynamic influence over soils and rocks and their excavation
	Preventive	Designs excluding suffosion caused by building or structure action. Removing of suffosion-prone soils and rocks
	Operative	Lowering of velocity of subsurface water flow. Correction of water-engineering structures operation especially of water intakes
	Barrier	Watertight screens and granular barriers. Organization of surface run-off. Filling of fractures and voids. Grouting

ANTI-SUFFOSION PROTECTION

Some of the techniques employed to protect buildings and structures from suffosion are shown in Table 1. In Moscow, civil engineering practice requires constructional protection of buildings against suffosional collapse sinks (Figure 10), in accordance with building regulations (Instruction... 1984).

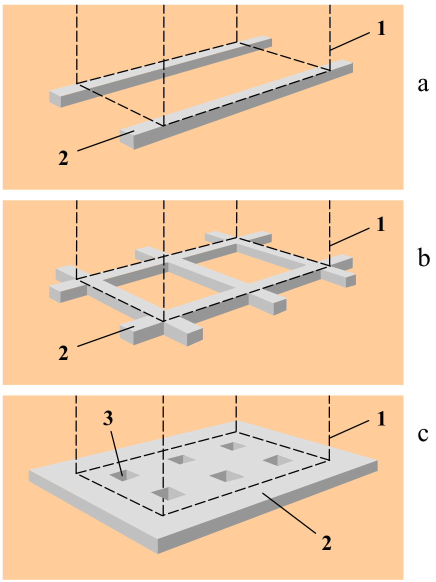


Figure 10. Types of foundations made of monolith steel concrete used in Moscow as constructional antisuffosinal protection (schematic). (a) Strips. (b) Crossing strips. (c) Slab
1. Contours of building. 2. Cantilever. 3. Slot for filling of collapse sink

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