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Forecasting the variation of loess soil properties due to underflooding in Novocherkassk, Russia

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Abstract: Novocherkassk, located in Rostov region of Russia, may be considered as one of the ten most environmentally problematic towns in Russia and has been designated as an ‘ecological emergency’, caused mainly by prolonged flooding (referred to as ‘underflooding’). This flooding has changed significantly the physical and mechanical properties of the ground, which in turn has caused damage to buildings and structures as well as the degradation of ecosystems. This paper documents the changes in ground properties caused by flooding in the ‘eastern housing district’ which is partially occupied by buildings. The main soil type covering the area is loess and loess rich clays (loams). The moisture content of these ranges from 13 to 31%, but flooding may increase this by approximately 8%. The liquidity (consistency) index (IL) shows broad variations and the solid, semi-solid and stiff-plastic soils may be changed to produce ‘soft-plastic’ and ‘flow-plastic’ consistencies. These may form as lenses, or may be interbedded within the soils and this can change significantly the properties of the original soils that were deposited during the Pleistocene and Holocene. Flooding can also reduce by about 50% the modulus of the total ground strain (E) producing weak ground conditions (<5 MPa). These types of ground conditions generate unfavourable engineering conditions which may ultimately result in subsidence (collapse or compression of the ground).

Résumé: Du point de vue de l'environnement Novotcherkassk (la région de Rostov) – est une de dix villes les plus malhanceuses de la Russie. Le territoire de la ville est une zone de la situation extraordinaire écologique. Telle situation est conditionnée, en particulier, par la montée puissante des eaux souterraines, qui est accompagnée par le changement des propriétés physico-mécaniques des terrains et, amène aux déformations des bâtiments et les constructions et provoque la dégradation des écosystèmes terrestres.

Le pronostic du changement des propriétés des terrains au cours de la montée future des eaux souterraines est réalisé pour plusieurs secteurs standard de la ville. L'attention principale est accordée aux grands ensembles d’Est qui sont au stade de projet, dont la partie considérable ne possède pas des bâtiments et se caractérise par les conditions géotechniques pareilles aux conditions naturelles. Le territoire est constitué par les terres argileuses de couverture qui sont déluviales et éolieno-déluviales loessiques et de loess. L'humidité des terrains changeait de 13 à 31 % pendant la période de l'étude. Dans le cas de la montée des eaux souterraines la signification de l'humidité augmentera en moyen de 8 % et, sa gamme du changement diminuera de 24 à 33 %.

Le paramètre de la fluidité (IL) changera plus considérablement. L'etat solide, semi-solide, difficilement plastique des alluvions étudiés est transformé en état à plasticité facile et fluante. On peut attendre aussi la formation des lentilles et des intercalations des terrains fluants. Au total, cela amènera à l'inversion de la variabilité spatiale naturelle IL formée au Pleistocène supérieur et à l'Holocène.

Le module de la déformation totale des terrains (E) au cours de la montée des eaux souterraines est deux fois plus petit que le module naturel, cependant seulement "en moyen". Cela amènera non seulement à l'inversion de la variabilité spatiale , mais aussi à la formation des terrains faibles (< 5 MPa).

Les changements des propriétés des terrains amèneront aux procès géotechniques négatifs dont le plus défavorable est subsidence.

Keywords: environmental geology, engineering geology, hydrogeology, loess, urban geosciences

INTRODUCTION

The city of Novocherkassk is located in the Rostov region of Russia and in 1993 it was designated as the capital of ‘the Cossacks’. It has a population of about 200,000 and occupies an area of about 126km^2. The city is situated in the south of the European part of Russia, about 40km northeast of Rostov-on-Don. Novocherkassk was founded 1805, as the capital of ‘Area of the Don Army’. The town is different from many of the classic Russian towns and it was based on the model for many typical European cities with; fine architecture, wide streets, public open spaces, parks, pubic squares, monuments, an impressive cathedral (known as Voznesensky Cathedral) and many areas of antiquity, culture and history.

Novocherkassk is one of the largest industrial towns of the North Caucasian area. It became an important industrial centre from 1930 to 1970. In 1932 engine and electro-locomotive manufacturing were established as a major industry. The industry grew in post World War times and more recently the main products have included electrodes, synthetic products, magnets and metal-cutting machine tools. These industrial processes have a detrimental impact on the atmosphere, surface and underground water supplies. Soils may be polluted by heavy metals, organic substances, mineral oil and others contaminant and this may effect agriculture. There has also been a negative affect on humans. For instance, birth rates have decreased, death rates have increased and the state of health of adults has deteriorated in recent years. Since the end of the 1980s and the start of the 1990s there have been reported cases of breathing difficulties, lung problems and malignant tumours. As a direct consequence Novocherkassk is now regarded in the top ten environmentally problematic cities in Russia and the situation is regarded as 'extreme' (Rodionova *et al.* 2001). These environmental effects are exacerbated by frequent, prolonged flooding.

Flooding in the urban environment can change the properties of soil which is dominated by loess. In order to reduce the detrimental impacts of this type of 'problem soil' it is desirable to predict the properties and engineering behaviour of the loess to prevent further damage and disruption to land and structures.

Geomorphological setting

Novocherkassk consists of two distinct basic parts: The southern part, known as the 'old city' or 'the Pervomaiskiy District' which occupies the elongate, eastern part of the Pontian Plateau. This is situated on the eastern bank of the River Don and reaches about 110 metres above ground level at Novocherkassk hill.

The northern part of the plateau is dissected by the River Tuzlov and in the east and south is the flood plain of the rivers Tuzlov and Aksay. The dominant superficial deposits are talus, aeolin talus and loess of Pliestocene age. These are 5 to 20m thick and were deposited on Scythian Clay of Pliocene age which is about 40m thick. Pontian Limestones of upper Neogene age underlie the clay, and below the limestone is Sarmatian clay of Miocene age. The depth to the water table is from 1 to 7.5m, but may be deeper on slopes.

The northern part of the city is dominated by industry and occupies the east bank terraces of the River Tuzlov. The superficial cover is mainly alluvium, talus, aeolian-talus and sandy loamy clay, these may reach 5 to 25m thick. These are lower Quaternary age and were deposited on clay bedrock of Oligocene age.

DESCRIPTION OF THE FLOODING (UNDERFLOODING)

The first available data on rising groundwater levels in the southern part of Novocherkassk dates back to 1911 to 1916. These rising groundwaters were envisaged to have been attributed to a combination of the geological structure of the region and climate control (Lisitsyn 1917). The start of intensive flooding dates back to the period 1950s to 1980s when the city underwent rapid growth and expansion. The changes in groundwater levels, from 1948 to 1961 are presented in Figure 1. This shows about an increase in the level of the water table of about 12m following the start of major construction and development in 1948. These were envisaged to have been caused by industrial processes rather than increased precipitation rates (Rodionova *et al.* 2001).

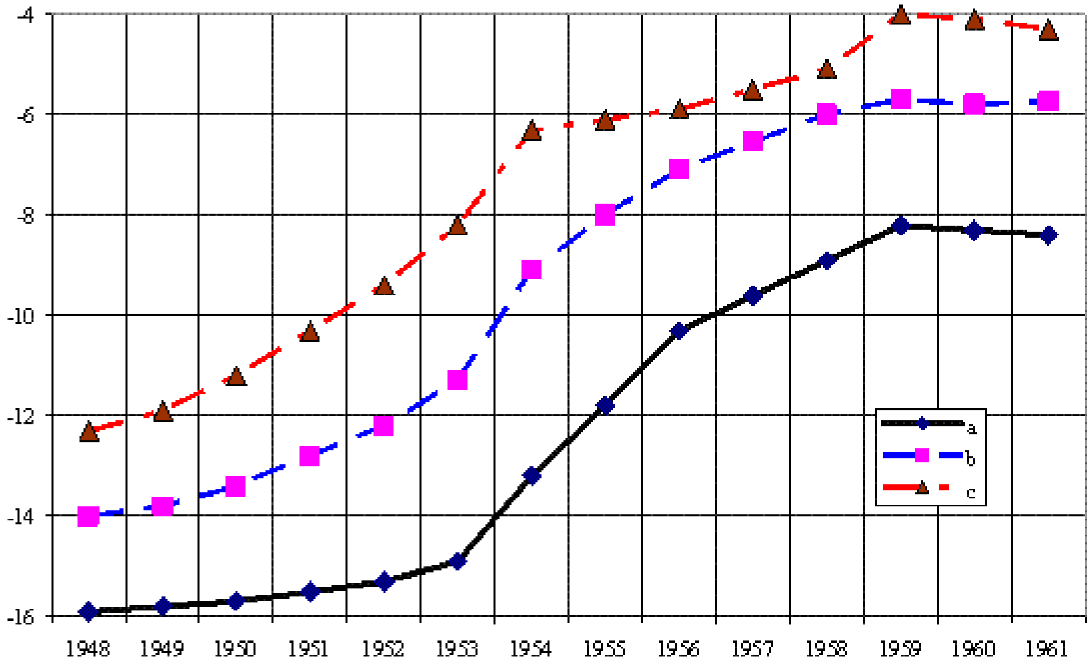

Figure 1. Changes in groundwater levels, at Novocherkassk, from 1948 to 1961 at; a) the southern part of the city; b) the central part of the city and c) the electrode factory. The horizontal axis represents time in years and the vertical axis shows groundwater depths in metres below ground level.

Groundwater levels are currently less than 5m below ground level for approximately 80% of the city. During the spring, flooding incidents increase and this is most notable in the industrialised areas. The variable depths of groundwater levels are illustrated in Figure 2.

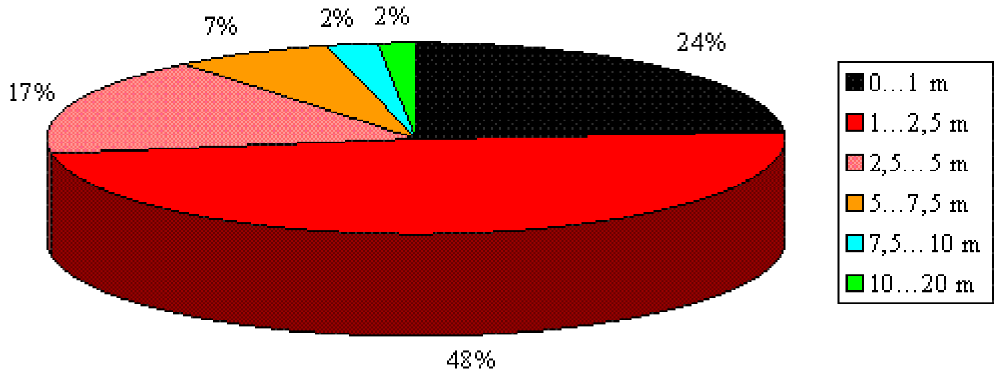

Figure 2. Illustration to show the depth to groundwater levels throughout the industrial parts of Novocherkassk during the spring period. The figures give the depth to groundwater in metres below ground level.

It can be seen from Figure 2 that almost half of the territory (48%) has groundwater levels which are 1 to 2.5m below ground level and 24% may be regarded as catastrophic, where groundwater levels are less than 1m below ground level. Where groundwater levels are 1 to 1.5m deep this causes flooding to cellars, basements and utilities. These groundwaters may also cause engineering problems, they may be aggressive to concrete foundations, cause deformation to structures and adversely affect ecosystems. Furthermore, the engineering and mechanical properties of soils and weak or weathered bedrock may also be changed by fluctuations in groundwater levels and (Murzenko *et al.* 2001).

EFFECT OF FLOODING ON THE ENGINEERING PROPERTIES OF THE GROUND

The effects of flooding and fluctuations in groundwater levels on the physical and mechanical properties of the ground have been investigated by (Kriger *et al.* 1981, Finaev, Domrachev & Rudchenko 1985, Vedernikov & Sokolov 1994). In particular investigations have been undertaken on the changes in the engineering properties and behaviour of Pleistocene loess and clay or silt rich loess since these underlie much of the city. Most of the investigations were undertaken from 1970 to 1993 when the most intense flooding took place. A summary of the main findings are given in Table 1 and Table 2.

Table 1. Changes in the properties of loess soils caused by flooding and fluctuations in groundwater levels (GL), depth (h) and thickness of soil (H). Moisture content (W) is given in %, ρ is soil density in g/cm3, compressibility and strain modulus at natural moisture is given as (En) and water content is given as Em (or may be expressed as a logarithm, εsl), porosity coefficient is expressed as e, IL is liquid limit, X is the average, Min is the minimal, Max is the maximal values, σx is the standard of x parameters

Parameters of distribution					Estimates of compactness of correlations (r, η)*				
		Min	Max	σ_x	h	lg H	GL	W	WL
h	-2,08	-22	12	5,33	*	0,86	0,50	0,58	0,28
H	7,10	1,0	28	4,70	-0,84	*	0,18	0,30	0,22
GL	5,03	0,1	14,8	2,91	0,48	0,10	*	0,40	0,17
W	22,2	7	40	4,24	-0,39	0,26	-0,37	*	0,38
WL	36,2	15	70	6,72	-0,13	0,12	-0,03	0,32	*
IL	0,08	-1,36	1,54	0,33	-0,30	0,18	-0,36	0,66	-0,39
ρ	1,90	1,47	2,20	0,11	-0,56	0,49	-0,30	0,20	-0,04
e	0,74	0,37	1,27	0,11	0,30	-0,32	0,07	0,36	0,27
Sr	0,82	0,27	1,09	0,15	-0,62	0,51	-0,42	0,69	0,08
$\log\varepsilon_{sl}$	-1,91	-2,30	-0,83	0,23	0,60	-0,51	0,36	-0,46	0,00
En	139	35	485	53,8	-0,35	0,36	-0,05	0,36	0,16
Em	98,7	17	273	40,8	-0,71	0,68	-0,20	0,22	-0,02

Table 2. Variations in ground parameters due to flooding.

Horizon	Models of relationships and property variations					
	W = f(e)	Sr = f(e)	IL = f(W)	En=f(W)	$\log\varepsilon_{sl}$ = f(W)	En = f(H)
I	4,0+27,7	1,04-0,2	0,04W-0,8	370-9,2W	-2,1+0,00W	119+3,5
II	10,6+12	1,09-0,5	0,06W-1,2	177-2,8W	-1,2-0,025W	109+3,0
III	15,6-0,2	1,09-0,7	0,06W-1,3	94+0,8W	-0,7-0,048W	102+1,5
I-III	11,9+14	1,23-0,6	0,05W-1,0	210-3,2W	-1,4-0,024W	110+4,1

Horizon	Gradient models of parameters behavior in property distribution				
	Sr = f(h)	σ_{Sr} = f(h)	A_{sr} = f(h)	$\log\varepsilon_{sl}$ = f(h)	$r_{\log\varepsilon_{sl-w}}$ = f(h)
I	0,88-0,003h	0,10+0,003h	-0,68-0,012h	-1,99+0,006h	-0,10-0,035h
II	0,79-0,035h	0,11+0,002h	-0,17+0,098h	-1,87+0,052h	-0,12-0,040h
III	0,57-0,002h	0,12+0,000h	0,38-0,023h	-1,57+0,006h	-0,31-0,014h
I-III	0,76-0,017h	0,10+0,003h	-0,19+0,040h	-1,82+0,025h	-0,11-0,035h

As a result of these investigations three main zones have been identified, these are as follows:

- Zone I: (where h <0m)
- Zone II: (where h 0-7.5m)
- Zone III: (where h >7.5m)

The above zones were used to investigate the relationship between the property indices and groundwater depth (h), where a linear relationship can be inferred (that is y = a + bx type). The regression coefficients (a, b) varied and had different h indices as follows:

- Liquid limit (IL) = 0.23 + 0.008h
- Liquid limit (IL) = 0.05 - 0.064h
- Liquid limit (IL) = -0.19 - 0.019h

It was found that there is a considerable time lag between flooding and the degradation affects on the soils. In some instances, more ‘recently’ flooded ground may still have some of the characteristics and properties of the original, undisturbed soil and this may be observed for 5 to 10 years after flooding has taken place. Although with time, all traces of the original fabric of the soil may be removed (Figure 3).

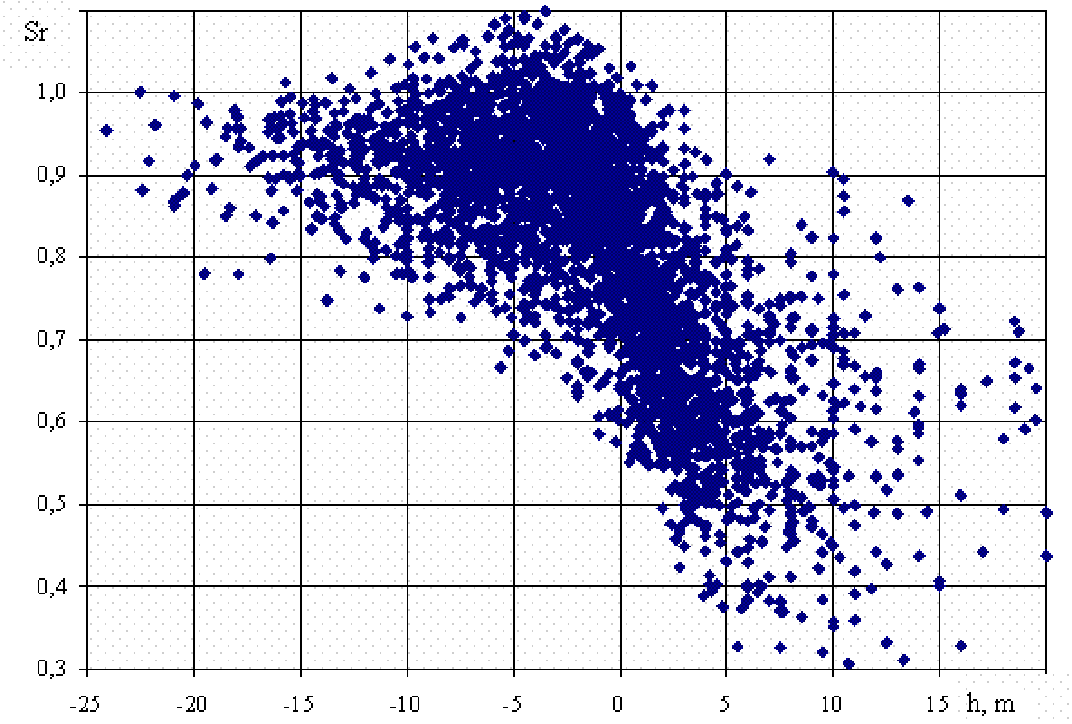

Figure 3. Correlation of moisture content of loess-clay (Sr) and groundwater depth (hm).

Figure 4 shows that the moisture content of loess-clay soils (Sr) remains constant during fluctuations in the groundwater levels from 1 to 19m below ground level. Other parameters of distribution and property relationship (ASr, rlogεsl-W, etc.) posses similar, sometimes higher sensitivity during change sin groundwater levels.

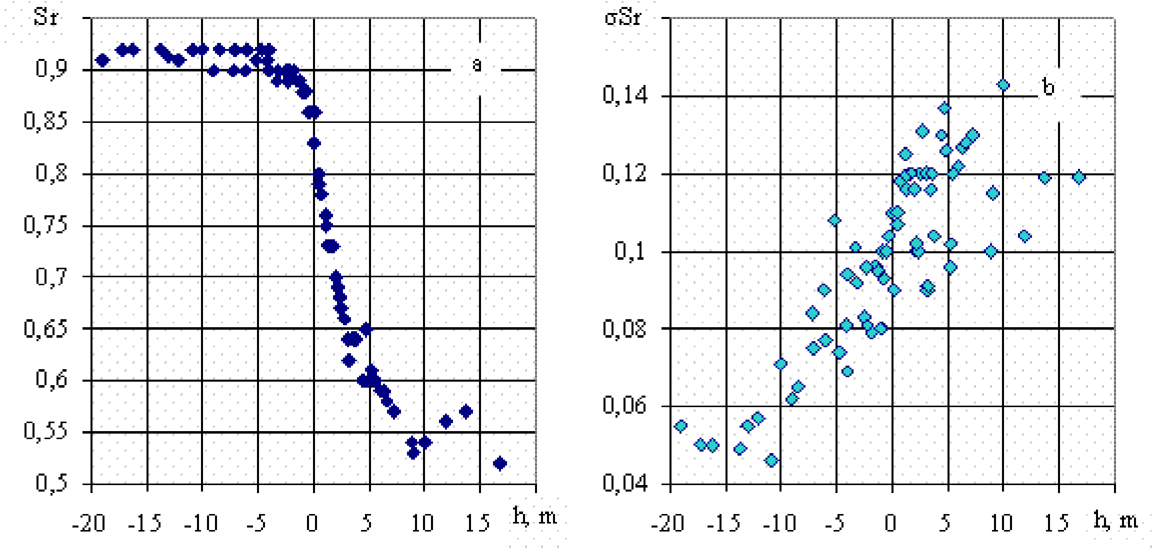

Figure 4. Change of key parameters of distribution of values of the degree of moisture content Sr (a) standards σ_{Sr} (b) depth to groundwater levels (h,m).

It was found that the flooding and ground water level fluctuations may be broadly grouped into three zones as follows.

- Completely natural (zone A)
- Partly caused by industry (zone B)
- Partly caused by industry (zone C)

At depths of 5.2 to 10m below ground level the 'wetted horizon' different mechanisms appear too operated. These include for example intensive saturation, partial saturation and slight moisture content, the former occurs as a 'film' on the soil. In terms of depth these occur at 0-2.8m, 2.8-5m and 5-7.5m respectively. Seven groundwater zones have been identified and these are given in Table 3 and Table 4.

Table 3. Changes in properties of loess soils at different depths below ground level.

Zone	Correlation coefficients					Models of property relationships		
	W-e	WW_L	ILW	E_k-W	Sr-e	W = f(e)	IL = f(W)	En=f(W)
	0,93	0,65	0,22	-0,72	0,01	0,2+33,7	0,015W-0,25	408-10W
B	0,80	0,32	0,34	-0,61	-0,25	3,8+28,4	0,032W-0,59	387-9,5W
C	0,73	0,25	0,55	-0,62	-0,24	5,0+26,1	0,046W-0,88	342-8,4W
D	0,49	0,22	0,72	-0,38	-0,32	7,8+17,5	0,060W-1,24	227-4,9W
E	0,23	0,33	0,65	-0,07	-0,57	13,4+6,1	0,053W-1,16	142-1,3W
F	0,23	0,46	0,69	0,01	-0,49	11,9+6,6	0,047W-1,10	111+0,2W
G	-0,05	0,02	0,66	0,04	-0,71	15,6-0,2	0,059W-1,27	94+0,8W

Table 4. Changes in behaviour of loess soils at different depths below ground level.

Zone	Sr = f(h)	A_{sr} = f(h)	σ_{Sr} = f(h)	$\log\varepsilon_{sl}$ = f(h)	$r_{\log\varepsilon sl\text{-}w}$ = f(h)
	0,92+0,000h	0,07+0,001h	0,01+0,035h	…	0,03-0,027h
B	0,91+0,001h	0,15+0,010h	-1,74-0,160h	-2,1+0,002h	-0,43-0,073h
C	0,86-0,014h	0,10+0,005h	-0,67-0,005h	-1,96+0,02h	-0,13-0,060h
D	0,84-0,068h	0,11+0,004h	-0,29+0,17h	-1,94+0,10h	-0,15-0,025h
E	0,63+0,000h	0,04+0,020h	-0,08+0,13h	-1,61-0,008h	0,23-0,136h
F	0,67-0,013h	0,03+0,014h	0,29-0,004h	-1,7+0,025h	0,74-0,177h
G	0,57-0,002h	0,12+0,000h	0,38-0,023h	-1,57+0,01h	-0,31-0,014h

It should be noted that maximal H variations in $\log\varepsilon_{sl}$ and En in E zone (-0.028H and 5.8H, respectively) have been determined. This is considered to be unfavourable for the building of structures and may lead to collapsing and compression (Tkachuk 2004).

FORECASTING VARIATIONS IN THE PROPERTIES OF LOESS SOIL DUE TO FLOODING

The results of the investigation demonstrate that loess soils are susceptible to degradation during flooding and this can change the physical and mechanical properties of the soil (Lomtadze 1984). These main changes appear to influence porosity, mineral composition, humidity (moisture content, W) liquidity index (IL), and the modulus of the ground strain (E). The critical depth where these changes take place was found to be in the zone 1.5 to 2.5m below ground level, although this varied depending on the local geology. The effects were particularly noted at, for example, the relatively smaller towns; Molodezhniy, Oktyabrskiy, the central part of Pervomaisky district.

In the 'eastern residential district' about 665 hectares of land occurs in a natural state and has not been built on. It is covered by aeolian-talus, loess and loess-like loams and their thickness ranging from 3 to 4 m in the south-western area (in the valley of River Tuzlov) and 15 to 23m in the north-west (near Tuzlov-Cadamov water shed). The covering loams are underlain by loess-talus and alluvial-talus of Pleistocene age. Groundwaters levels are at 1 to 3m deep in the southwest and 15m in the northwest part of the territory. During October to December 1992 investigations were undertaken were and the soil humidity was found to vary from 13 to 31%. It is anticipated that flooding and rises in groundwater levels increase the moisture content (W) by an average of 8% in the south-western part of the region, but the increase in the northern and western part is negligible. It is also expected that the engineering behaviour of the soil will change from solid, semi-solid and stiff-plastic consistencies to soft-plastic and flow-plastic consistencies (Figure 5). These types of changes to the properties of the soil are likely to result in an increase in the compressibility, or collapse of the soil, resulting in subsidence.

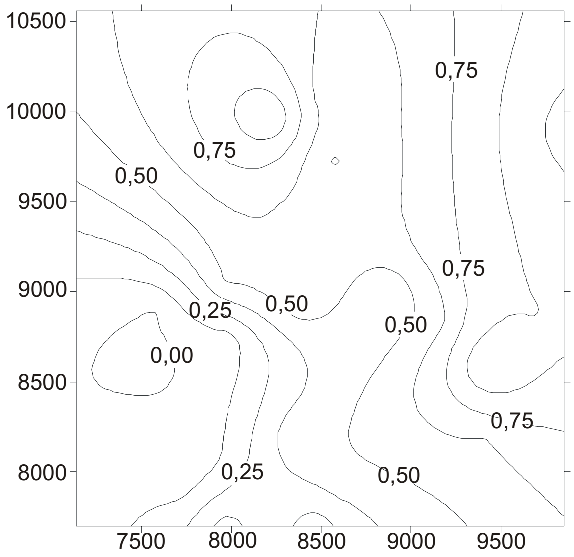

Figure 5. Schematic map to show the changes in liquidity index during flooding for the ground in the Eastern microdistrict of Novocherkassk.

FORECASTING COLLAPSE & COMPRESION (SUBSIDENCE) OF LOESS

An estimation of the areas of possible soil collapse and/or compression, resulting in subsidence of the ground, was undertaken to assist with the design of foundations. The depth of the foundations for buildings and other structures was considered to be 2m below ground level. The depth of the potentially collapsible soil was considered to be not lower than the minimal height of the water capillary rise in the ground (about 1.5m and usually no more 10.5m). The forecasting of the potential collapse of buildings and foundations in the 'eastern microdistrict' was carried out in two parts; under a loading of 0.3 MPa and the buildings own weight (Ananyev & Gilman 1993). In parts of the region there were two small areas where collapse was predicted to exceed 15cm, If the loading is equal to 0.3 MPa, i.e. at a considerable low loading, a small collapse may occur in the central part of the territory while in its north-eastern part collapse can become 30cm or greater. In the central part of Pervomaiskiy district ground movements are considerably lower (7.3cm on the average).

This estimation of 'subsidence' caused by lowering of groundwater was based on Hook's law which states a direct proportional dependence of stress and relative strain. As the ground water level becomes lower the effective stresses increase. Below the groundwater level hydrostatic weighing is removed, which on the whole leads to the strain causing subsidence mentioned above (Dashko 1987). It has been estimated that subsidence may occur throughout Novocherkassk caused by decreased groundwater levels, but this will be variable. The highest values are observed in the 'NSPP territory' ($S5 = 13.9$cm) (Figure 6).

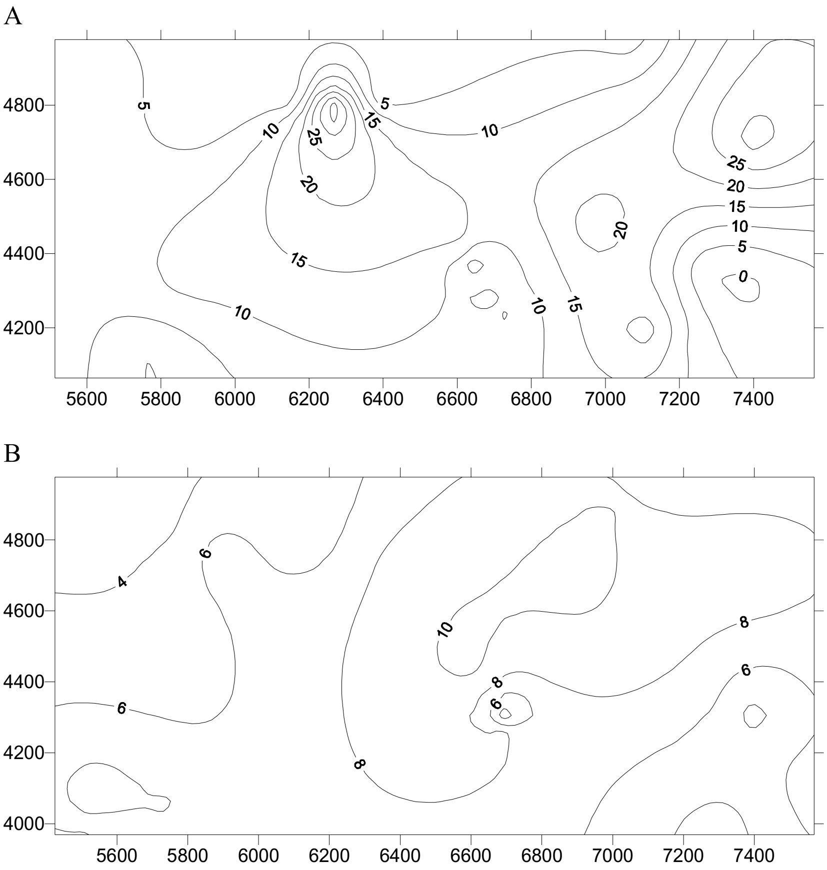

Figure 6. Schematic map of maximum possible collapse for building foundations; (A) subsidence of the ground surface with 5m lower of groundwater levels (B) the central part of Pervomaiskiy district of Novocherkassk.

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