LIQUEFACTION-INDUCED FLOW SLIDE IN THE COLLAPSIBLE LOESS DEPOSIT IN SOVIET TAJIK

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ABSTRACT

In the suburb of Dushanbe, Tajikistan Republic of USSR, an earthquake of magnitude 5.5 took place on January 23, 1989. In this event, extensive liquefaction developed in the loess deposit of aeolian origin in the gently sloping hilly terrain and led to a series of catastrophic landslides accompanied by a large-scale mud flow. In contrast to the hitherto known cases of liquefaction which have usually occurred in water-sedimented sand deposits, the liquefaction in Tajik was unique and novel in that it occurred unexpectedly in a wind-laid deposit of silt in a semi-arid region. The reasons for such a liquefaction are thought to be the collapsible nature of highly porous loessal silt which had been wetted by irrigation water over the past years. The complete collapse of the loess structure due to the additional action of the seismic shaking appears to have led to the catastrophic landslide. In addition, the silt-sized soil constituting the loess was of low plasticity and hence could easily slump and flow through a distance as long as 2.0 km.

Key words: earthquake, liquefaction, loess, silt (IGC: B 4/C 9/E 8)

INTRODUCTION

Development of liquefaction and consequent occurrence of slumping or flow slides in sandy deposits have been recognized as the major phenomena leading to catastrophic damage to the ground during earthquakes. Actual cases of such failure have been reported by many investigators (Dobry and Alvarez, 1967; Seed, 1987; Ishihara et al., 1990). Most of the cases ever encountered, however, involved liquefaction-induced flow slides in the deposits sedimanted under water, whether placed artificially or naturally. Thus, the studies of in-situ liquefaction have been mainly on those cases which occurred in lowland areas in the waterfront or in deposits underlying water-retaining embankments or dams.

It was, therefore, a great surprise to observe a series of catastrophic flow slides which took place during the recent earthquake in nearly flat terrain in a semi-arid region where the ground is covered by a thick mantle of silts of aeolian origin. The earthquake occurred

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in the suburb of Dushanbe, capital city of Tajikistan Republic in USSR, and the liquefaction induced thereby triggered a chain of landslides leading to a catastrophic mud flow. This event seems to be unique and previously unknown phenomenon. Thus, in the following pages, the new features of the earthquake and the liquefaction-induced mud flow will be described, together with the mechanism of liquefaction occurring in the collapsible loess deposit.

TAJIK EARTHQUAKE OF JANUARY 1989

At 5:02 a.m. on January 23, 1989, an earthquake with a magnitude 5.5 shook a village area called Gissar about 30 km southwest of Dushanbe, the capital of the Tajikistan Republic of USSR which borders on Afghanistan.

The location of the epicenter is shown in the map of Fig. 1. The focal depth of this event is reported to have been about 35 km. As shown in Fig. 2, the affected area is located on a relatively flat basin-like plain which developed in front of the southern flank of the Pamir mountain range. The Dushanbe river flows southward on a fan deposit through the city of Dushanbe and merges into the Kahrinighan river as shown in Fig. 3. The epicentral area is located at Gissar near the junction of the Kahrinighan river and the Halaka river. The tremor was felt over the epicentral area and a network of strong motion seismographs registered the motions at several stations, as indicated in Fig. 4. In the city of Dushanbe, the peak
horizontal ground accelerations during the main shock were of the order of 50 to 90 gal. The time histories of acceleration recorded at Cymbiliff closest to the epicenter are shown in Fig. 5, where it can be seen that the main shaking lasted for about 4 seconds with a peak acceleration of 125 gal in the north–south direction. Extrapolating from the magnitude of recorded motions in its vicinity, the epicentral area is supposed to have undergone a shaking with a peak ground acceleration of the order of 150 gal. In view of its magnitude of shaking and the moderate degree of observed structural damage, the intensity of shaking at the epicentral area is estimated to have been 7 in MSK (Soviet scale in 12 degree), as accordingly indicated in Fig. 4. Class 7 in MSK is equivalent to the class 7 in Modified Mercalli scale in USA and to the class 4 in terms of the Japanese Meteorological Agency scale. The occurrence of the earthquake is purported to be associated with a fault movement of the order of 30 cm as indicated in Fig. 3, but it was not possible for the authors to trace any clearly visible

Fig. 5. Horizontal accelerations during the main shock of the earthquake

Fig. 6. Plan view of the slide area in Gissar
evidence of the fault on the ground surface.

LANDSLIDE AND DEBRIS FLOW

In the village of Gissar, there are about 500 farmer's houses and barns constructed of woods with adobe type walls. Even in the most severely affected area, the degree of structural damage was such that houses were partially destroyed and thus the destruction due to the earthquake shaking itself was moderate and limited to small local area.

The most striking feature of the damage was a series of landslides and debris flow
which took place over the gently sloping hilly terrain consisting of windblown deposits "loess". There were four landslides in the affected area of Gissar as indicated in plan view of Fig. 6. The landslides turned into a mud flow of vast scale and buried more than 100 houses in 5 meters of mud. An estimated 220 villagers died or were missing in the debris.

1) Sharara Slide

The landslide at Sharara is about 800 m in frontage and the debris spread out as far downward as 300 m from the original toe of the hill as shown in Fig. 7. Many houses in the village immediately downhill was buried in mud resulting in the largest number of casualties. A view looking northward from the top of the bluff is shown in the photograph in Fig. 8, where two water storage tanks are seen perching on the debris. These tanks had been installed on the hilltop to supply water for domestic use and for agricultural irrigation. Just beyond the scarp of the slide on the east side, a pumping station remains intact as indicated in Fig. 7. The pumping station was used to pump up water to the storage tanks or directly to the water channel for irrigation. Approximate cross sections of the slide are shown in Fig. 9, where it may be seen that the broken blocks of loess soil moved out and turned into debris flow. The depth of sliding surface is estimated to be about 30 m at the bluff line. It is to be noticed that the bluff line produced by the Sharara slide is almost coincident with the line of the water channel installed on the shoulder of the hill to supply water for the farmland over the hills. Thus, it appears likely that the water in the channel had been infiltrating into the loess deposit over the years and slide was initiated from the failure of loess soils near the channel weakened by water invation. In fact, near the distal end of the debris flow, muddy water was seen spurting and oozing from amid fragmented pieces of the loessal soils.

2) Firma Slide

The site of the Firma slide is located about 500 m west of the Sharara slide as shown in Fig. 10. This slide, having developed along the same shoulder line, appears to be a continuation of the slide at Sharara. Thus, the features and conditions of the occurrence of this slide are almost identical to those at Sharara explained above. In fact, a small ditch about 1.0 m wide and 0.5 m deep had been excavated along the scarp line to supply water for the
farmland on the gently sloping hills back of the scarp line. Thus, the loessal soils wetted by water infiltration appear to have been responsible for causing the slide during the earthquake. As shown in a cross section in Fig. 11, there was a considerable spreading of the soil mass, extending outward about 100 m from the toe of the slide. This characteristic feature is indicative of the fact that a considerable amount of water was involved in the sliding mass of soils. Considerable ground cracking was produced over the hill slopes extending about 50 m rearward from the slide scarp, indicating that overall movement of soils took place over a relatively wide area behind the slide. A photograph looking southward at the scarp is shown in Fig. 12. It can be seen that the scarp is nearly vertical indicative of the fact that the soil block fell off from vertical cleavage of fissures.
3) **May 1 Slide**

The location of a small slide in the hamlet of May 1 is indicated in Fig. 13. This slide encompasses an area approximately 100 m in width and 100 m in length. As shown in a cross section of Fig. 14, the slide scarp is located at the shoulder of a hill where an unlined water channel about 3 m wide and 2 m deep was excavated. As was the case with the other slides, the water invasion into the loess deposit appears to have weakened the soil prior to the advent of the seismic shaking. Unlike the other slides, a pressure ridge about 7 m high was formed at the toe, because
of the buttress action of the firm ground in front of the slide. The pressure ridge is clearly seen in the photograph in Fig. 15.

At the bottom of a chink between broken blocks of soil as indicated in Fig. 13, a cone penetration test was conducted by means of a portable hand cone test device. The cone has an apex angle of 30° and a cross sectional area of 3.23 cm². The result of the cone test is presented in Fig. 16 in terms of the penetration resistance, \(q_c\)-value, plotted versus depth. It may be seen that the cone resistance is about 12 kg/cm² at a depth of about 2 m from the bottom of the chink where the sliding zone appears to have developed.

4) Okuli Slide

The largest and most cataclysmic phenomenon was the multiple slides at Okuli which developed in a slightly depressed area over hilly farmlands. The plan view of the slide is shown in Fig. 6. The genetic portion of the slide extends westward over a length of about 1.5 km from the escarpment at the east (see Fig. 17). Taking into account the fact that the slide encompasses an area about 850 m in frontage and 15 m in depth on the average, the total volume of the soil mass is estimated to be approximately 20 million cubic meters. At least two slides seem to have been triggered independently from the hillsides on
initially induced at the toe might have retrogressed backwards over a distance of 1.5 km to the east and sidewards to the north as well as to the south. Over the rugged sliding area, the original ground was broken into many blocks producing an extremely irregular and hummocky surface. Amid broken blocks, there were spreads of soil mud having presumably sprung out of the in-depth sliding zone, suggesting that liquefaction of saturated loess soil occurred during the earthquake. The sliding mass of the loess soil turned into a huge-scale debris flow and travelled through a distance of about 2 km on nearly flat surface of the ground. The debris covered an area as large as about 1.5 million square meters, as indicated in Fig. 6. Near the distal tongue of the debris flow at Okuli-po'en, tens of farmer’s houses and barns were buried in

Fig. 17. A view from the north over the eastern escarpment of Okuli slide

the north which then merged into the main stream of the mud flow. The shallow slide indicated by B in Fig. 6 took place on the terrace of high relief with its scarp located near the hilltop and after the soil moved over the gentle slope the debris flow jumped into the main stream. There were many traces of violent mud flow remaining on the exposed hard soils, indicating evidence of liquefaction and consequent muddy flow of loess soil during the earthquake (see Fig. 18). The slides indicated by A and C in Fig. 6 appear to have been initiated along the line of the water channel. It appears likely that a small slide 2 to 5 meters of mud. A photograph in Fig. 19 shows buried houses near the end of the debris.

Several cone penetration tests were performed on the rugged surface, as indicated in Fig. 6, by means of the same portable cone device as used in the May 1 slide area. Typical results of the cone tests are shown in Fig. 20, where it may be seen that in the sliding zone at depths of about 7 to 8 m, $q_c$-value was found to be about $1 \sim 5 \text{ kgf/cm}^2$. 
SOIL CONDITIONS IN THE AFFECTED AREA

The area affected by the earthquake has a topography of gently sloping hilly terrain. The terrain is covered by a mantle of loess which was deposited windblown from Karakum desert west of Tajikistan and Kirgistan Republics during the Pleistocene era. The windlaid material is silt and tan to light-brown in color. The soil conditions in this area were investigated by the Geological Bureau of Tajikistan Academy of Science in Dushanbe. The soil profile in the north-south cross section in the middle of the slide area (B-B' section in Fig. 6) is shown in Fig. 21. The cross section along the longitudinal direction of the slide (A-A' section in
Fig. 20. Cone penetration test results at Okuli slide area

Fig. 21. North-south cross section B-B' in Fig. 6

Fig. 6) is presented in Fig. 22. It may be seen that the loess deposit covers the ground surface to a depth of about 30 to 40 m, underlain by gravelly sand which varies in thickness to a maximum of 200 m.

The results of investigations by the Geological Bureau of Tajikistan Academy of Science show that the ground water table is located about 5 m from the ground surface, but the water content diminishes around the depth of 20 m which is underlain by dry layers of the loess. It is also reported that, while the layer of loess about 3 m in thickness below the ground water table has a water content of about 20%, the loess layer below this level does possess a higher water content with a maximum of 40%. The zone of such a highly saturated layer of loess is indicated in Figs. 21 and 22. On the other hand, the laboratory tests have shown that the liquid limit and plastic limit of the loess is around 30 and 20, respectively, giving a value of about 10 for the plasticity index. Thus, the natural water content of the highly saturated loess is in excess of the liquid limit. Fig. 23 shows the grain size distribution curve of the loess. It may be seen that the loess is comprised of 80% of silt and 15% of clay fraction, and that
CHARACTERISTICS OF LOESS DEPOSITS

It is well known that windblown deposits of soils characteristically possess vertical cleavage planes and, therefore, when a deposit is excavated, soil blocks tend to fall off leaving nearly vertical scarps. In steep-sided gullies in the windlaid deposit, splitting off of columnar sections of soil blocks is commonly observed. The wind-deposited loess in Gissar is no exception and there are vertical scarps developing widely along the head line of the slides in Sharara, Firma, May 1 and Okuli. It is also known (Clevenger, 1958; Dudley, 1970; Chen, 1987) that the windlaid loess is tan to light brown in color, light-weight and consists of matrix of cemented silt with a number of interspersed macro and micro pores which are purported to be remains of root holes. Generally, the loess deposit is devoid of clear stratification and is highly crumbly and brittle in a dry state, being powdered easily between fingers. The loess is known to be composed of silt-sized particles of quartz and feldspars bonded together by a small fraction of montmorillonite-type clay. As is generally the case, the loess in Gissar area contains about 15% clay as indicated by the gradation curve in Fig. 23. The loess is known as a material having a matrix structure which is collapsible when wetted with water. When maintained dry, it is reasonably strong and incompressible and the porous structure may persist even under a fairly large overburden pressure. However, once wetted, the loess may lose its stability. Because of its highly porous nature, water can easily infiltrate into the pores, whereby breaking down the matrix structure. As a result, a significant amount of decrease in bulk volume and loss of shear strength can take place under sustained loads, leading to large settlements or failure of structures founded on such loess deposits. This kind of characteristics is often referred to as hydraulic collapsibility.

Another feature of engineering significance is the fact that disturbed loess is of low-plasticity with its Atterberg limits plotting near the A-line in the plasticity chart. The
plasticity index of the loess is generally around 10. Thus, if collapse is triggered with a sufficient amount of water invasion in excess of the liquid limit, the disturbed loess being devoid of cohesion tends to easily slump and flow. It is known that any soil with a low plasticity index has a great potential to develop liquefaction and flow-type failure (Ishihara and Koseki, 1989).

With the above mentioned several characteristics of the loess taken together, it is expected with good reasons that the loess deposits in Gissar area had been invaded with a large quantity of water prior to the earthquake and narrowly on the verge of hydraulic collapse, and when subjected to the seismic shock loading, it spontaneously developed liquefaction and resulting mud flow.

**MECHANISM OF LIQUEFACTION AND DEBRIS FLOW**

The lands in the Gissar area had been left uncultivated through geological time. However, with the recent development of township and increasing population in the urban area of Dushanbe, the lands have been cultivated and used as agricultural farmlands to produce wheat and cotton. To match the needs for water supply in the agricultural lands, a network of water channels was constructed in the hilly area in Gissar. Some sections of the water canal were lined with concrete but most were unlined. The water for irrigation was pumped up to the hilltop, and was distributed to each patch of farmlands from two large storage tanks or, directly through a network of open canals. The water in the canals had been leaking and permeating into the ground through the vertical fissures in the loess deposit over the years and the large quantity of absorbed water had been filling up the pores in the loess. As indicated schematically in Fig. 24, the ground water table was found to lie about 5 m from the ground surface but the water content of the loess at a depth greater than about 20 m was found to be small. It was also discovered that the water content in the layer between depths of about 7 m and 17 m is greater than the liquid limit. Thus, the water content might have probably been distributed throughout the depth of the loess deposit as shown in Fig. 24. At depths a few meters below the ground water table, the pores of the loess were probably only partly filled with water, but as the water pressure increased with increasing depth, the pores probably became fully saturated, producing a state of oversaturation with a water content in excess of the liquid limit. The exact depth of the vertical cleavage in the loess deposit is not known, but the maximum depth at which vertical cracks can remain open may be inferred by comparing the vertical overburden pressure with the uniaxial compressional strength of the soil element, as illustrated in Fig. 25. Suppose the vertical stress at depth \( Z \) given by \( \gamma_t Z \) exceeds the uniaxial compressional strength, \( q_u \), then the soil element at this depth will fail whereby producing a large deformation in the lateral direction. If there exists an open crack to this depth, it would be closed by this lateral bulge. Therefore, the depth at which a crack is closed may be given by,

\[
Z \geq \frac{q_u}{\gamma_t}
\]

(1)

where \( \gamma_t \) is unit weight of the soil. The exact value of the uniaxial compressional strength of the loess at Gissar is not known, but in view of the cementation developed in the matrix structure, the strength may be inferred roughly to be within the range of \( q_u = 200 \sim 400 \text{ kN/m}^2 \). Then, assuming the unit weight to be approximately \( \gamma_t = 15 \text{ kN/m}^2 \), the depth of crack penetration is estimated to be about 15 to 25 m. Considering a dominant role played by the openness or closure of cracks, the gross permeability of the loess deposit would probably have been distributed through the depth as shown in Fig. 24. It is to be noted that, at the depth between 15 and 20 m, the permeability coefficient decreases sharply, prohibiting the water from migrating farther into the deeper portion of the deposit. This would account for the fact that the measured water content in the deeper deposit was small of the order of 10\%. By retaining a large quantity of water, the loess deposits between the depths
of about 7 and 17 m appear to have been in a state of impending hydraulic collapse even prior to the advent of the earthquake. In fact, it is reported that a noticeable amount of ground settlements had been observed over the surface of the firmland even prior to the advent of the earthquake. This fact indicates that the hydraulic collapse had partially occurred in the loess deposit in this area. However, since the topography in Gissar area is so gentle, that the downslope component of the gravity force was not large enough to cause landsliding and therefore the ground remained stable as a whole before the occurrence of the earthquake. When the earthquake occurred in this area, the saturated loess already in a precarious state underwent shaking and total collapse of the loess structure was provoked, leading to liquefaction of the silt-sized material. Moreover, because of the low-plasticity of the silt, the liquefied silt began to flow out even on a nearly flat ground surface, carrying large masses of soil. In the case of the slide in Okuli, the mud flow travelled through a distance of 2.0 km as indicated in Fig. 6. In the Okuli slide, the slide appears to have started first in a small section adjacent to the toe, and a series of sequential slides must have retrogressed from one section to another until it reached the place of the final escarpment on the east. This type of progressive failure is likely to develop in soils which require only small magnitude of driving force to cause failure. It is to be noted that no landslide and mud flow in such a gentle slope would indeed take place with such a large scale except by the shaking of an earthquake.
SIMPLE ANALYSIS FOR LIQUEFACTION

It is apparent that the liquefaction in the loess deposit was caused by the combined action of water infiltration and seismic shaking. The loess deposit had been in a metastable state on the verge of complete failure due to the invasion of water and as such even a small magnitude of seismic shock would be great enough to produce a state of liquefaction and a consequent catastrophic mud flow. Thus, when examining the triggering mechanism, any analysis of liquefaction will require a knowledge of cyclic resistance of the loess which has been soaked to a precarious state in which the hydraulic collapse is about to take place. The cyclic resistance of a loess in such a state has not been investigated and, in addition, in the absence of any data from in-situ penetration tests in the loess deposit in Gissar area, it is difficult to estimate the cyclic resistance of the intact loess except by means of a back analysis based on a known intensity of shaking during the earthquake. The back analysis to evaluate the cyclic strength can be made by calculating the maximum shear stress ratio, \( \frac{\tau_{\text{max}}}{\sigma'_v} \), through the formula,

\[
\frac{\tau_{\text{max}}}{\sigma'_v} = \frac{a_{\text{max}}}{g} (1 - 0.015 Z) \frac{\sigma_v}{\sigma'_v} \quad (2)
\]

where \( a_{\text{max}} \) denotes a peak value in an irregular time history of acceleration on the ground surface, \( \tau_{\text{max}} \) is a corresponding peak value of dynamic shear stress acting on a horizontal plane at depth \( Z \). \( g \) is the gravity acceleration. \( \sigma_v \) and \( \sigma'_v \) indicate the total and effective vertical stress at depth \( Z \), respectively.

In the present case, the maximum acceleration is inferred to have been of the order of 150 gal, based on the data recorded at Cymbulif about 5 km southwest of the epicenter as indicated in Fig. 4. The depth at which liquefaction was triggered may be taken typically as being about 10 m. Thus, the total and effective vertical stress are computed to be \( \sigma_v = 160 \text{ kN/m}^2 \) and \( \sigma'_v = 110 \text{ kN/m}^2 \), respectively, assuming the unit weight is \( \gamma_v = 15 \text{ kN/m}^3 \). With these values inserted in Eq. (2) the maximum stress ratio is obtained as

\[
\frac{\tau_{\text{max}}}{\sigma'_v} = 0.185 \quad (3)
\]

This value may be taken as being equal to the maximum stress ratio required to trigger the liquefaction in the loess deposit. The strength as above may be alternatively expressed in terms of the cyclic stress ratio causing liquefaction in 20 cycles of load application. For this transformation, the mean effective confining stress or the confining stress in the equivalent triaxial test condition, \( \sigma'_v \), is calculated as \( \sigma'_v = (1 + 2 K_0) \sigma'_v / 3 \), where \( K_0 \) is the coefficient of earth pressure at rest. The value of \( K_0 \) at this particular location is not known, but in view of the wind-laid type of the loess deposit, it may be assumed that the soil had been normally consolidated and hence the value of \( K_0 \) was approximately equal to 0.5. Thus, the confining stress is calculated as \( \sigma'_v = 2/3 \cdot \sigma'_v \). In view of the shock-like time history of the seismic shaking as shown in Fig. 5, a correction factor of 0.55 may be used to obtain an equivalent amplitude of cyclic axial stress, \( \sigma_{dt} \), required to cause liquefaction in 20 cycles in the triaxial loading condition (Ishihara, 1977). Thus, in terms of the cyclic stress ratio causing liquefaction in 20 cycles, the value in Eq. (3) is expressed as

\[
\left( \frac{\sigma_{dt}}{2 \sigma'_v} \right)_{20} = 0.55 \times 2 \times \frac{\tau_{\text{max}}}{\sigma'_v} = 0.153 \quad (4)
\]

This value is approximately equal to the cyclic strength of loose Toyoura sand compacted to a relative density of about 30%.

STABILITY ANALYSIS FOR FLOW SLIDE

In all the slides in the Gissar as described above, it is apparent that the flow–type failure took place following the triggering of liquefaction. By considering the geometry of the mud flow it is possible to conduct post-earthquake stability analysis and to back-estimate the residual strength or steady-state strength of the liquefied loess material (Ishihara et al. 1990). This analysis consists of back-calculating values of undrained shear stress of soils,
Table 1. Results of post-earthquake stability analysis

<table>
<thead>
<tr>
<th>Site</th>
<th>Average depth H (m)</th>
<th>Average slope θ (degree)</th>
<th>Residual strength Su (kN/m²)</th>
<th>Cone resistance qc (kN/cm²)</th>
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<td>9</td>
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<td>(A-A section)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Firma</td>
<td>7</td>
<td>13</td>
<td>14.5</td>
<td>—</td>
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<td>May 1</td>
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<td>12</td>
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<td>3 ~ 6</td>
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CONCLUSIONS

At the time of the 1989 January 23 earthquake in the suburb of Dushanbe, Tajikistan Republic of USSR, liquefaction developed in the aeolian loess deposit and resulted in a series of landslides accompanied by a large-scale mud flow. The occurrence of liquefaction is attributed to the highly collapsible nature of porous loess deposits which had been wetted to a depth of about 15 m by water used for agricultural irrigation. The wind-laid loess consisting mainly of silt-sized soil is thought to have been in a barely stable state on the verge of hydraulic collapse before the earthquake, and this led easily to a complete collapse in a form of liquefaction upon being further subjected to seismic shaking. The complete slumping and long-distance flowage of the mud on the nearly flat ground was explained by the fact that the loess-forming silt is of low plasticity with a plasticity index of about 10. The result of the post-stability analyses made for four sites of landslides in Gissar indicated the mobilized undrained residual strength of the silt to have been probably in the range between 2.0 and 15.0 kN/m² which approximately coincides with similarly evaluated values of residual strength in other case studies of flow failures.

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