Paper No. 663

GEOTECHNICAL EVALUATION OF A MORNING GLORY SPILLWAY FAILURE FOUNDED ON EXPANSIVE AND DISPERSIVE CLAY

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ABSTRACT

Surla dam, an irrigation/storage dam was constructed in 1985 across a small river in Chakwal area of Potohar Plateau of Pakistan. A morning glory spillway structure was constructed on right abutment of the dam for handling excess/flood water. The morning glory lip and upper concrete slabs of glacis and stilling basin are resting on shale type foundation material where as the lower concrete slabs of glacis rest on sand stone. The morning glory lip and the upper concrete slabs of glacis resting on shale experienced severe cracking upon first ponding of the reservoir. During first flood, foundation was severely eroded by water leaving large cavities under the slabs. In fact some of the slabs were washed down into the river. This required expensive repair works in the form of back filling of foundation material and replacement of concrete slabs. A research was recently conducted at National University of Sciences and Technology, Risalpur Campus (Pakistan) to determine the causes of this failure. This paper presents findings of this research study. Since similar problematic soils exist in the entire northern part of the country, this study aimed at investigating such problematic soils so as the practicing engineers can benefit from this information while planning and executing irrigation/storage structure projects in similar geologic environments. Based on site investigations, lab testing and subsequent analysis of data it is concluded that the spillway structure failed due to expansive nature of the foundation material. The laboratory investigations confirmed that the clays of Surla are expansive in nature. The expansive clays of Surla dam area, when provided access to water, are capable of exerting an upward swelling pressure of more than 1 Kg/cm^2. The concrete slab is exerting down ward pressure of 0.1Kg/cm^2 due to its self weight. This difference in upward and downward pressure resulted in a system of forces that caused uplift pressures on the concrete slabs thereby resulting into extensive cracking. The lab results have also confirmed the highly dispersive nature of Surla clay. During floods water entered the foundation through cracks resulting in extensive erosion of the structure. Eventually large cavities were formed which resulted in sagging of the concrete slabs at a number of places under their own weight. The outcome of the study demonstrates that inadequate site investigations lead to serious damage and costly repairs. It is concluded that pinhole test is very useful to predict

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erodability of clay soils and must be performed on all such soils used as foundation material for water retention structures. Additionally it is concluded that Odometer test performed on undisturbed samples yields valuable information pertaining to swelling behavior and shall be performed on foundation material of such prestigious projects.

KEYWORDS: Spillway failure, swelling clays, erodable soils, foundation heave

INTRODUCTION

Surla Dam is a 25 m high, 250 m long, homogeneous earthen dam resulting in a reservoir with gross storage of 2 million m^3 (Surla Dam Project Report, 1976). A typical cross section of Surla dam is presented in Fig. 1a. An impervious clay core has been provided in the middle of the section to act as a water barrier. The core rests on bedrock that was accessed by stripping off 2 to 3 m of over burden material. The core is flanked by homogeneous shells sloping at 1:3 on U/S (up stream) side and 2.5:1 on D/S side (Project completion Report, Surla Dam, 1986).

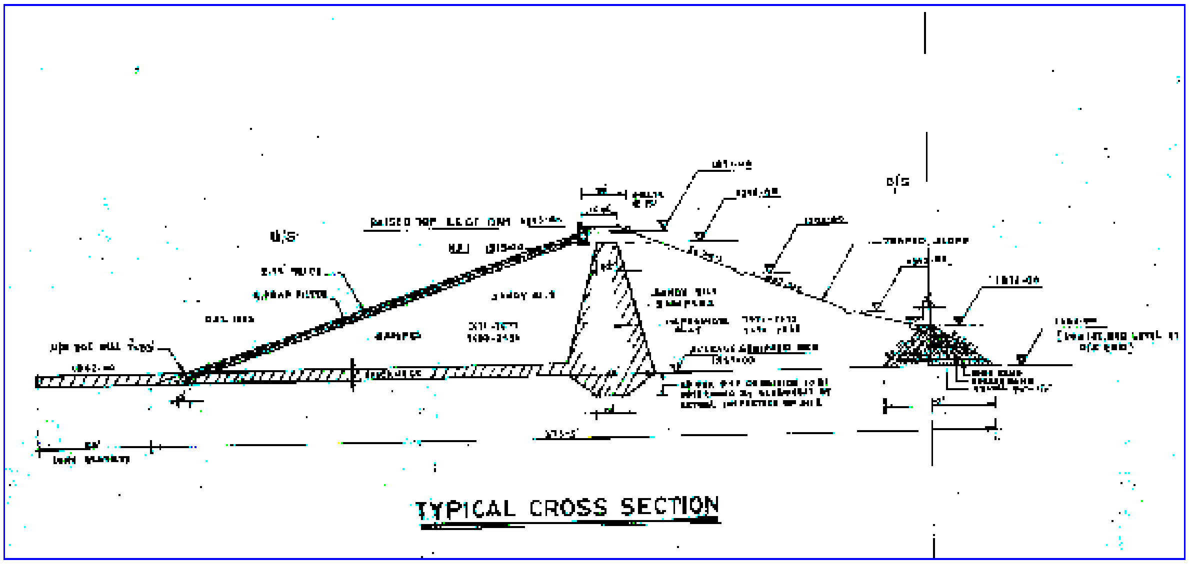

Fig 1(a). Typical dam cross section

Records show that detailed investigations pertaining to site geology, construction materials, hydrology, irrigation requirements etc., were carried out prior to initiation of the project. During geologic studies a number of pits were excavated in the main dam and the spillway area. Three boreholes were made along the dam axis, one in the riverbed and one each on either abutment. The right abutment and centre hole was drilled vertically up to 30 m where as the left abutment hole was 40 m deep inclined at 30 degrees with the vertical. Water pressure tests were conducted in all of these holes through out their length to determine permeability of strata. These tests were not successful either due to caving or due to leakage through the packer. General field observations revealed alternating beds of sandstone and clay at the dam site. Sandstone beds are generally soft to moderately hard while clay beds are generally weak in nature. Prior to dam construction most of the area now under embankment was covered with overburden. Main overburden material comprised of silty sand and was generally in the form of terraces. Area that formed the slopes was generally covered with scree and overlaid clay beds. Geologists concluded that the dam site is simple and no complex structural anomaly was noted. The general strike orientation was observed to be across the river flow and was recorded as N72W. It was concluded that the beds are generally dipping towards NE direction i.e. downstream side with an average angle of 25 degrees. Some of the outcrops on the left abutment did not show any distinct orientation due to cover of overburden but the general strike trend and some of the exposed beds indicated that the beds were more or less conformable ruling out any possibility of structural complexity.

A concrete spillway structure has been provided to cater for floodwater. The spillway structure has been constructed on the right abutment about 200 m U/S of the main body of the dam by cutting through a ridge. The spillway structure consists of a morning glory type lip with semicircular crest and gently sloping glacis (Figure 1b&c).

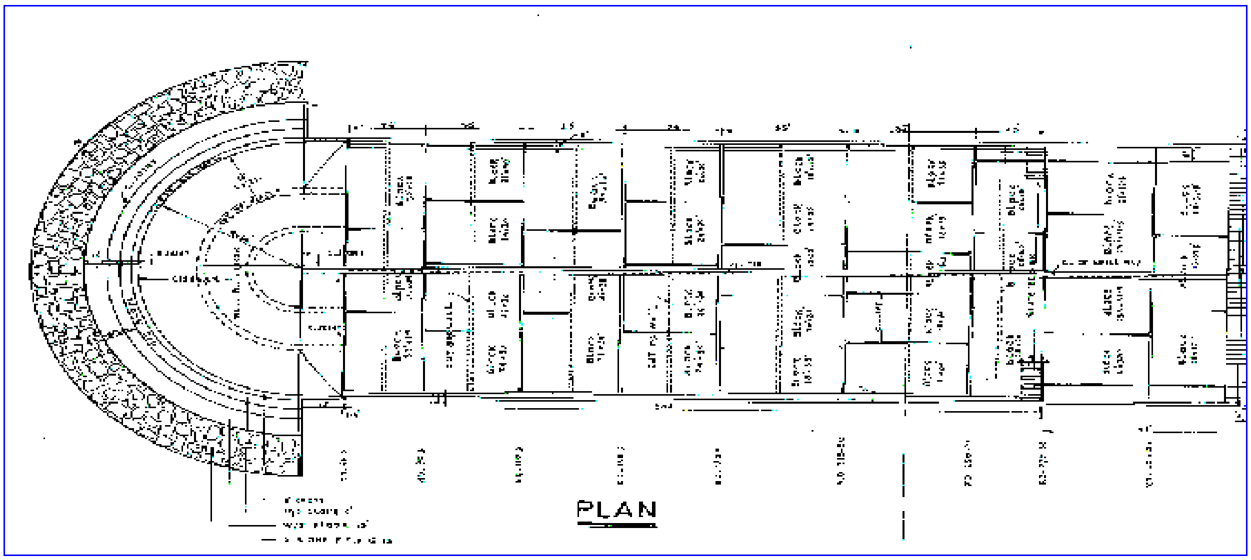

Figure 1(b) Plan view of the spillway (pl. blow up for details)

A stilling basin has been provided at the down stream end of the spillway to induce hydraulic jump for proper dissipation of energy. Two bore holes were put down in the spillway area and it was concluded that the rock units in the spillway area are the same as those at the dam site i.e., alternating beds of sandstone and clay are present in the spillway area as well. The alignment of the spillway structure is across the strike direction. The concrete spillway structure rests mostly on clay beds except for the last two rows of concrete panels and stilling basin that rest on sandstone bed.

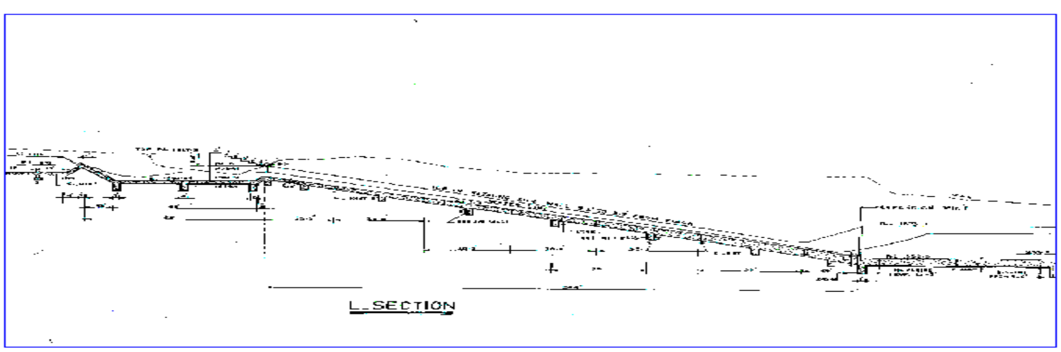

Figure 1(c). Cross section of the spillway (pl. blow up for details)

During first event of spill the spillway structure experienced swear distress. Most of the concrete slabs resting on clay were washed down and expensive repairs were required to salvage the project. This paper reports findings of the investigations undertaken to determine causes of spillway failure.

FIELD & LABORATORY TESTING RESULTS

Three locations at site, two on the upstream of the semi circular crest and one on the right abutment just next to the stilling basin were selected for the collection of undisturbed block samples and in situ testing. The samples were taken out from the shale type foundation material that has not been subjected to moisture change due to ponding. The field tests were also conducted on the same material. The index tests yielded a liquid limit of 40, Plastic limit of 18 and shrinkage limit of 13. The hydrometric analysis indicated that the soil contains approximately 25 % clay. The activity of the Surla shale therefore comes out to be 1.10. The soil classifies as Clay of low plasticity.

Standard penetration tests conducted on the foundation material yielded average blow count of 40 for 3 m depth. The corresponding allowable bearing capacity is 4.8 kg/cm^2 under undisturbed state. The same soil yielded a low blow count of 7 when the foundation was saturated yielding allowable bearing capacity of 0.7 kg/cm^2. Equation proposed by Peck et al., (1974) for 25 mm settlement was used for these computations. Plate Load test conducted in the field in dry conditions on the U/S of the spillway crest yielded ultimate bearing capacity of 11.4 kg/cm^2 corresponding to 25mm settlement (Fig 2). Unconfined Compression test was conducted on nine undisturbed specimens carefully carved out of block sample. These tests yielded average unconfined compression strength of 12 kg/cm^2 which is in conformance with the results obtained from SPT and plate load test. Unconsolidated Undrained Triaxial Tests were conducted on two specimens. These specimens were saturated prior to shearing and yielded undrained strength of 0.9 kg/cm^2. This indicates that saturation of this material can cause ten times reduction in compressive strength. Free *swell test (Katzir & David, 1968, Das, B.M, 1990) was conducted in the odometer cell* under a small surcharge of 0.07 kg/cm^2. The test was conducted on two specimens (Fig 3) and for each the specimen swelled from original height of 20 mm to 22 mm. The swell is, therefore, 2 mm and the value of free swell comes out to be 10%. The swell pressure of Surla shale was determined through the *restrained swell test. The* specimen was placed in an odometer under a small surcharge of about 0.07 kg/cm^2. The load on the specimen was increased periodically after it was inundated so that the height of the specimen remained constant. The vertical stress necessary to maintain Zero volume change is the swelling pressure. When this test was conducted on Surla clay it yielded a swell pressure of 1kg/cm^2. The final moisture content of the specimen was 14.4 %.

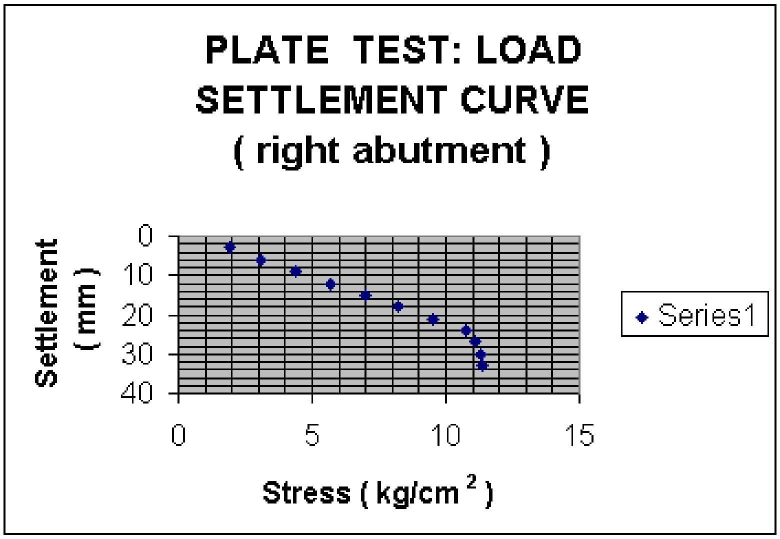

Figure 2. Results of plate load test

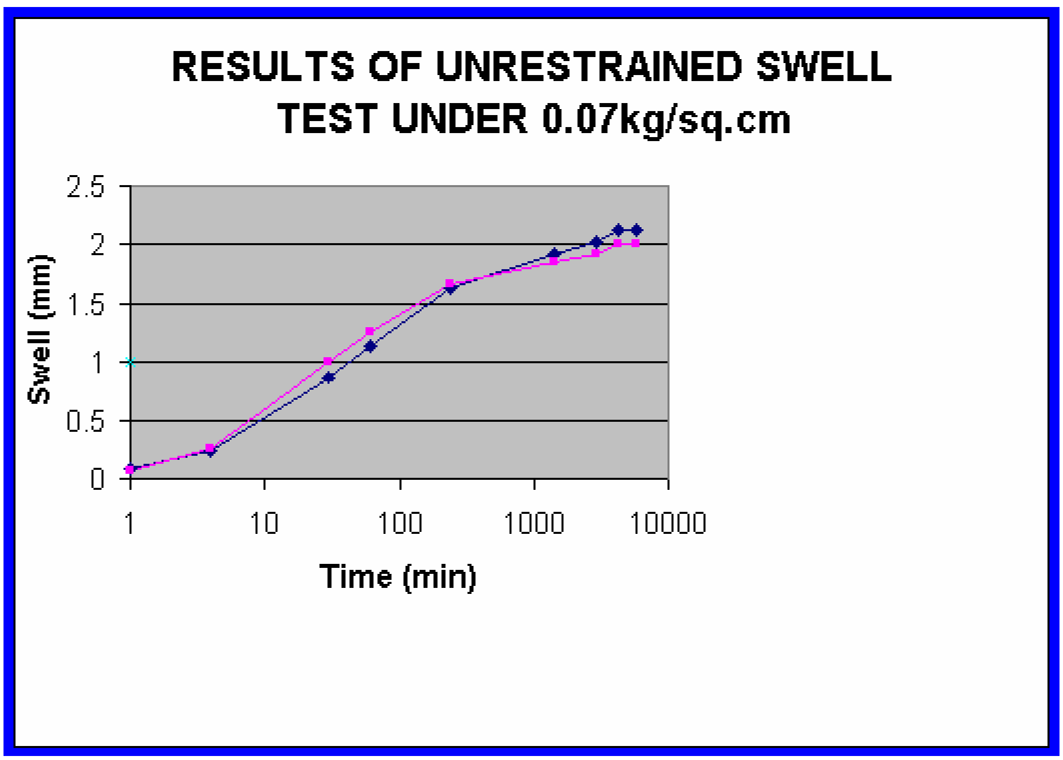

Figure 3. Results of unrestrained swell test

A number of unrestrained swell tests were also conducted on Surla clay. An initial pressure of 0.1 kg/cm ^{2} was applied over each specimen to simulate field loading from the concrete slab. The specimen was inundated and allowed to swell. Once the swelling seized the specimen was loaded. The pressure required to bring back the specimen to the original height is the swelling pressure. Typical test results reported in Fig. 4 and Fig. 5 indicate that the average swell pressure is 2 kg/cm^2. The swell pressure from this test is roughly twice the swell pressure from the constrained swell test. The average value of a_V & C_C was determined to be 0.005 cm^2/kg and 0.2 respectively. Pinhole test (ASTM, 1998, Sherard etal., 1976) was also conducted on Surla clay to determine the erodability or dispersion potential. When the sample was subjected to 5 cm of head the out flowing water experienced a colour change implying that soil particles were coming out. Thus the soil has high erodability potential and is classified as D1 according to ASTM specifications.

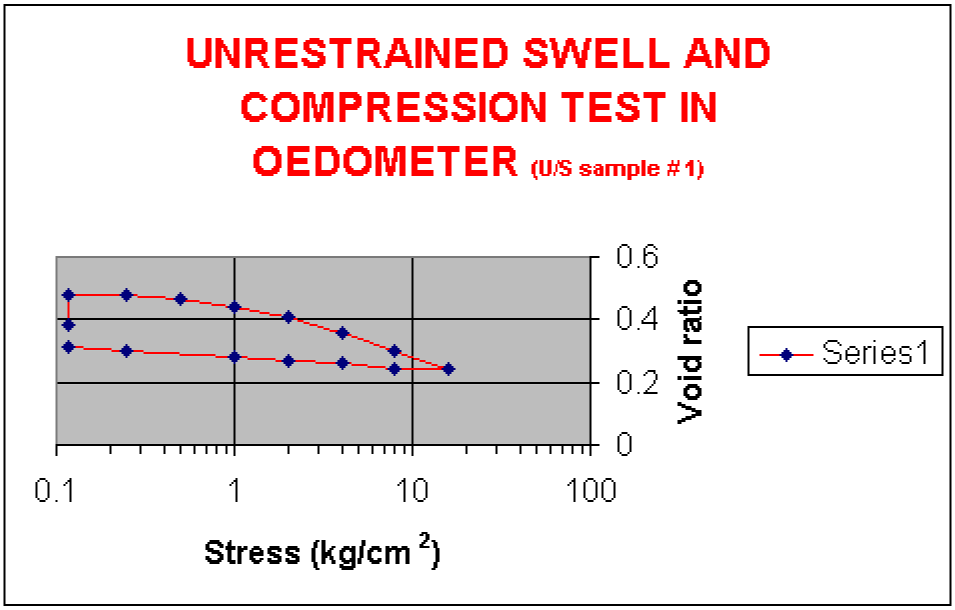

Figure 4. Results of unrestrained swell and compression test in Oedometer

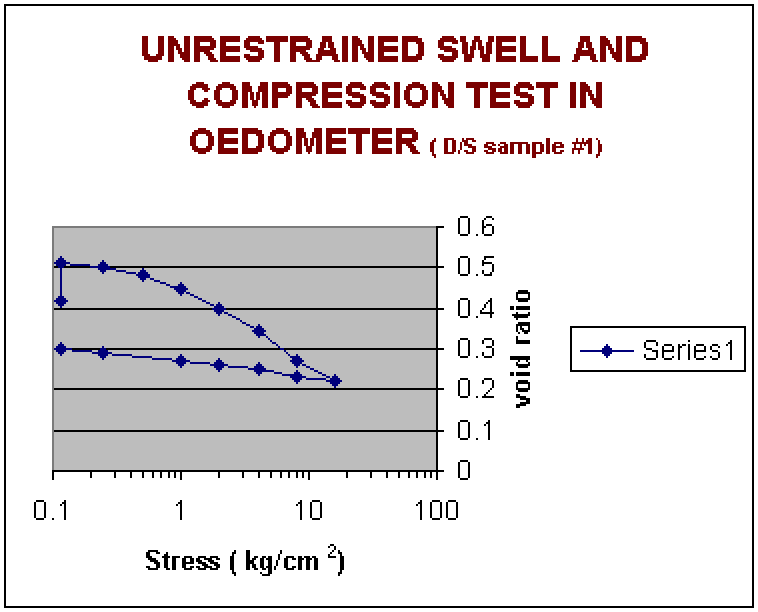

Figure 5. Results of unrestrained swell and compression test in Oedometer

ANALYSIS OF LAB & FIELD TEST RESULTS

The region is frequented by collapsible soils and it was speculated that failure of spillway occurred due to soil collapse upon saturation. The consolidation test was performed on undisturbed samples collected from the U/S, middle and D/S portions of the spillway. These tests were expected to show collapse of soil structure upon saturation. On the contrary the soil expanded when it was saturated thus establishing that the foundation material is expansive clay. A number of methods and soil tests were used to confirm swelling characteristics of Surla dam clays. These included swelling tests and other simple laboratory tests and correlations with the classification and index properties of the soil. Swelling clays characteristically possess high liquid limit and plasticity Index. For the range of plasticity index of 15 to 28 and shrinkage limit of 10 to 16 the probable expansion of the soil is in the medium range. Thus the clay at Surla dam has medium swelling potential. Similarly when the liquid limit and in situ dry density of surla clay (40 and 1950 kg/m^3 respectively) were plotted on the curve proposed by Mitchell and Gardener (1975) , the Surla clay plots as medium expansive(Figure 6). Seed, etal. (1962) developed the relationships (Fig.7) for artificial mixtures of sands and clays compacted to maximum unit weight by standard Proctor compaction and allowed to swell against a 6.9 kPa (1 psi) surcharge. These relationships between activity and percent clay sizes have also been shown to be applicable to natural soils. The purpose of Figure 7 is to identify a potentially swelling soil, which may require further study and tests such as an expansion or swell test. As per this graph Surla dam clay has medium swell potential. Based on *modified free* swell index for clays, as suggested by Sivapullaiah, Sitharam, and Rao (1987), the modified free swell index for Surla clay is 3.54 thus indicating that the soil has moderate swelling potential.

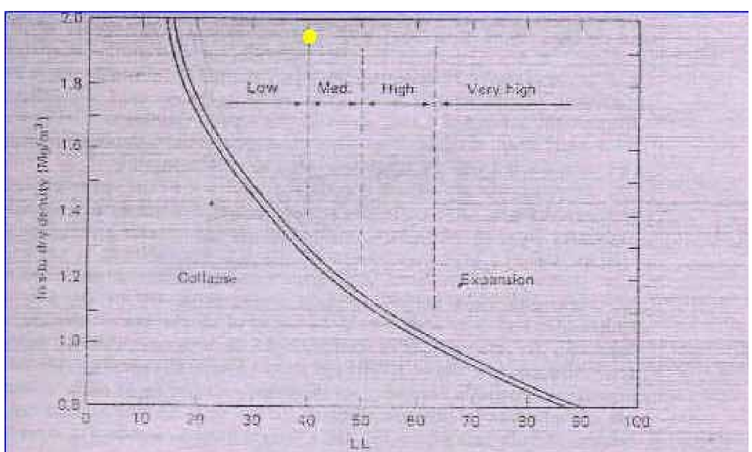

Fig. 6.14 Guide to collapsibility, compressibility, and expansion based on in situ dry densities and the liquid limit (adapted from Mitchell and Gardner, 1975, and Gibbs, 1969).

Figure 6. Liquid limit and in situ dry density of surla clay plotted on the curve proposed by Mitchell and Gardener (1975)

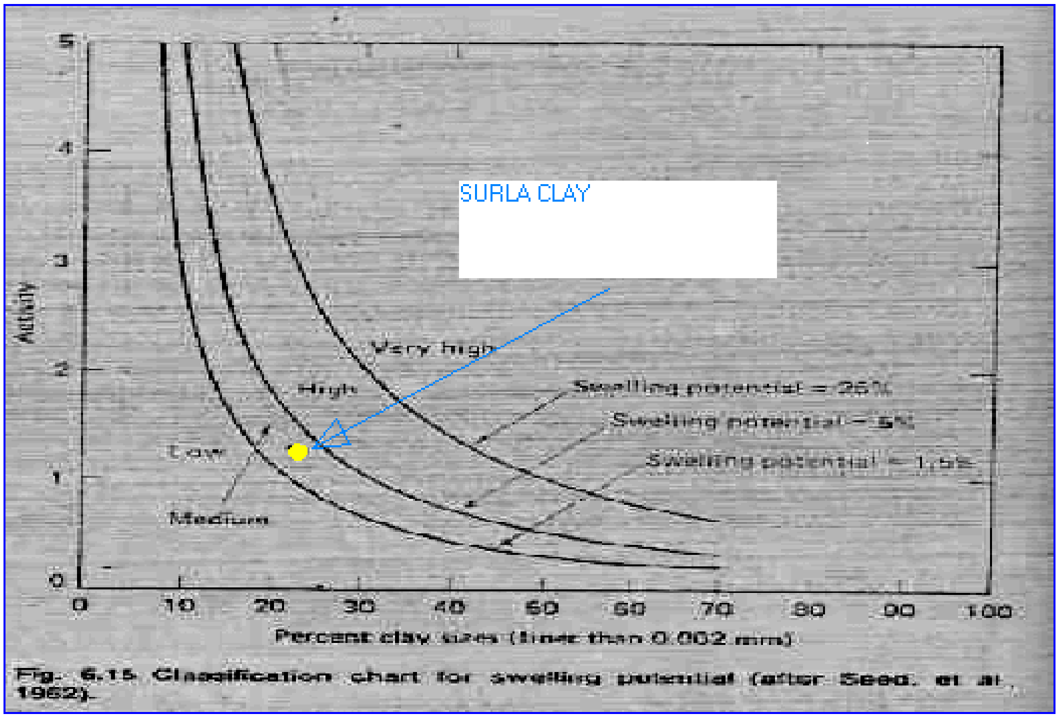

Figure 7. Identification of potentially swelling soils using activity & % clay

These results confirm that the Tables and curves developed by various agencies and researchers are reasonably accurate for predicting swelling potential of a soil based on simple index tests. Unconfined compression, SPT and plate load tests were conducted at site to determine the bearing capacity of soil under saturated and unsaturated states. Allowable bearing capacity of the soil in its unsaturated undisturbed state is very high i.e., 4 kg/cm^2. Standard Penetration Tests and plate load Tests under saturated conditions were also conducted in situ by pre-wetting foundation material. These results also yielded a bearing capacity much in excess of the pressure applied by the self weight of the structure i.e., 0.1 kg/cm^2. Triaxial tests were conducted on undisturbed samples in saturated state to determine the bearing capacity of foundation material in saturated state to model foundation saturation after impoundment of reservoir yielding allowable bearing capacity of 0.34 kg/cm^2. It implies that the spillway is safe against soil bearing failure and some other mechanism caused distress.

ANALYSIS OF SPILLWAY FAILURE

As stated earlier the morning glory spillway structure at Surla dam is resting on alternate beds of shale and sand stone. The concrete spillway structure was constructed after excavating a deep trench in the right abutment of the main dam. The concrete structure rests on shale in its upper portion where as the last two rows of concrete panels for sloping glacis and stilling basin rest on sand stone and weakly cemented conglomerate beds. At the top the thickness of the concrete slab is only 0.5 m that increases gradually down the slope of glacis. The downward pressure exerted by the self weight of slab, therefore comes out to be around 0.1 kg/cm^2. As stated above the foundation is safe against bearing capacity failure. Oedometer tests (Fig 4 & 5)conducted on specimen prepared from undisturbed block specimens yielded most important results that seem to provide insight into failure mechanism. Results of all specimens collected from U/S, center and D/S portions of the spillway yielded similar results i.e., the soil expanded when it was exposed to water. The free swell of specimens was in the order of 10 %. Another set of Odometer tests indicated that the swelling pressure for the foundation material of Surla dam spillway is 1.0 kg/cm^2. This swell pressure is roughly ten times the downward pressure being exerted by the slab itself. This explains the lifting of slabs upon first filling of the reservoir for it is well known that swelling can initiate failure (Hudson, J.A and Harrison, J.D, 1997; Katzir & David 1968 ; Franklin, J.A and Dusseault, M.B 1989). Swelling of foundation shale upon exposure to moisture definitely took place. The heavy cracking of the slabs and possible opening up of joints can easily be visualized if the process of first ponding is taken into consideration. As water was stored in the reservoir for the first time, a waterfront within the foundation soil started to move towards the spillway structure. One can conceive that the waterfront started to move from U/S of the spillway towards its D/S end. Since the permeability of the foundation clay is reasonably low, in the order of 10^{-5} cm/s , it is speculated that the movement of this front was slow. As soon as the foundation material under the concreted U/S portion of the spillway received water it expanded or swelled. The swelling clay exerted uplift pressure on the slab whereas the slab tried to contain this expansion. The D/S portion of foundation soil, however, was not exposed to water due to slow movement of the waterfront and thus remained unaffected. This resulted in a pressure distribution on the slab whereby the upper portion of the concrete structure was subjected to uplift forces and the down stream portion experienced only down ward pressure due to self-weight. At some point along the structure the overturning forces were sufficiently high to cause cracking of the concrete slab reinforced with temperature steel only. This process continued as waterfront moved downstream and all slabs resting on shale experienced substantial heaving and subsequent cracking. These conclusions are further augmented by the fact that at site the concrete slabs resting on the sand stone and conglomerate beds have not experienced any distress. The foundation of these slabs is stable and therefore these slabs did not experience any damage. The situation was further aggravated by the dispersive nature of foundation soil. As already stated the soil is highly erodable. During first flood as soon as the high velocity water passed over the morning glory crest and sloping glacis, it entered the crevices and started eroding the foundation. Dispersive clay did not offer any resistance to scouring. Subsequently large caverns were formed right under the concrete slabs. Since the slabs have been provided with only temperature steel on the top, they were damaged heavily after removal of the support from the ground. Some of these were washed down the glacis into the stilling basin. The presence of natural deep cavities and under ground caverns in close vicinity of the spillway structure confirms the dispersive nature of Surla shale and testifies the findings of this study. Expensive repairs to spillway structure were subsequently required to prevent complete destruction of spillway and failure of project.

CONCLUSIONS

Based on site investigations, lab testing and subsequent analysis of data it is concluded that following are the causes of Surla dam morning glory spillway failure. Such causes can result into severe damage/failure of such structures on similar soils.

Increase in moisture content of foundation soil upon filling of reservoir with water: No measures were adopted to check ingress of water towards the expansive foundation material. In case no measures are adopted to check ingress of water towards the expansive foundation material then this can result in uplift pressures thereby causing damage/failure.

Expansive nature of the foundation material: spillway structure is resting on expansive clay that expands appreciably when exposed to moisture.

Exertion of uplift swelling pressure on concrete slabs of the morning glory structure: The expansive clay of Surla can exert an upward swelling pressure in excess of 1 Kg/cm^2 whereas the slab itself is exerting down ward pressure of 0.1Kg/cm^2 only. Due to slow waterfront movement, the upward thrust did not act over the entire structure resulting in differential loading causing cracking of the concrete structure.

Erosion of foundation material: Surla dam clay is highly dispersive in nature. Cracking of structure initially occurred due to swelling pressure. When floodwater passed over the slabs it entered underneath them through cracks and started eroding the foundation clay. Due to highly dispersive nature of clay, the foundation did not offer any resistance to erosion and large caverns were formed under the concrete structure. The slabs subsequently sagged-in under their own weight and were washed down into the river.

Insufficient geo-technical investigations: Insufficient geo-technical investigations were carried out prior to commencement of project. It appears that only geologists were involved in geotechnical investigation and pertinent soil tests generally recommended by geotechnical engineers for such formations were not given due consideration.

Geologist’s observations : Proper attention was not given to geologist’s observation regarding loss of water in the boreholes while performing permeability tests using packers. This loss of water was attributed to difficulty in setting packers whereas the problem was due to erosion of soil along the packers thus causing leakage.

The sandstone beds were not properly utilized : Locating the structure entirely sandstone beds could have ensured safety. Alternately, chemical stabilization with lime might have been considered to reduce the swelling of expansive clays. Under reamed piles or special type of waffle slabs may be adopted for such soils.

Pinhole test: pinhole test is very useful for predicting dispersion and erodability of clay and must be performed on all clay type foundation materials for water retention structures.

Index properties: Liquid limit, plastic limit and activity can reasonably well predict swelling behavior when existing tables and curves are used. Further more Odometer test yields valuable information pertaining to swelling behavior and shall be performed on foundation material of all important projects.

Swell pressure: The swell pressure from the unrestrained swell test is roughly twice the swell pressure from the constrained swell test. In this study unrestrained swell test was conducted under a load that simulates the field conditions and is more appropriate for designing foundations resting on swelling clays.

REFERENCES

1. ASTM, Annual Book of ASTM Standards, Vol 04.08, 1998
2. Das , B.M., 1990 "Principles of Foundation Engineering" PWS - KENT , USA
3. Franklin, J.A and Dusseault, M.B., 1989 "Rock Engineering", Mc Graw Hill , Inc.
4. Hudson, J.A and Harrison, J.D., 1997; "An introduction to the principles of Engineering Rock Mechanics" Elsevier Science Inc. NY USA
5. Katzir, M & David, P., 1968, "Foundations on Expansive Marls", Proc. 2nd. Int. Research in Eng. Conf. on Expansive Clay Soils, Texas.
6. Mitchell, J.K., and Gardener, W.S. (1975) "In Situ Measurement of Volume change Characteristics", State of the Art Report, Proceedings of ASCE Specialty conference on In Situ Measurement of Soil Properties, Raleigh, North Carolina, Vol II, pp 333.
7. Peck R.B., Hanson, W.E., and Thornburn, T. H. (1974) Foundation Engineering, Second edition ., Wiley, New York.
8. Seed, H.B., Woodward, R. J and Lundgren, R. 1962, " Prediction of Swelling Potential for Compacted Clays", Journal of Soil Mechanics and Foundation Divn, ASCE, Vol 88, No. SM3, pp 107 – 131.
9. Sivapullaiah, P.V., Sitharam, J.G. and Rao, K.S.S. 1987, "Modified Free Swell Index for Clays". Geotechnical Testing Journal, American Society for Testing and Materials, Vol.11, No.2, PP 80 - 85
10. Sherard,J.L., et al., "Pinhole Test for Identification of Dispersive Soils," J. Geotech. Eng. Div., ASCE, Vol 102, No. GT-4, 1976 , pp 69 - 85
11. Sherard,J.L., et al., "Identification and Nature of Dispersive Soils," J. Geotech. Eng. Div., ASCE, Vol 102, No. GT-4, 1976 , pp 287 - 301

12. Surla Dam Project Report, 1985, Small Dams Organization, Dept. of Power & Irrigation, Govt. of Punjab.