Strength parameters for the Karameh dam foundations
Resistance des fondations du barrage de Karameh

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SYNOPSIS: The Karameh foundation soils consist primarily of calcite and aragonite deposits which are often thinly interlaminated. Conventional behaviour could not be presupposed for these materials, many of which are sensitive to remoulding and which led to concern regarding their dynamic behaviour. The impounding of a freshwater reservoir will fundamentally change the chemistry of the environment. Investigations, including both conventional and special laboratory testing, were designed and implemented to determine with confidence long term shear strength parameters for the dam foundation soils.

1 INTRODUCTION

The proposed Karameh Dam Project comprises the construction of a major storage reservoir in Wadi Mallaha which lies adjacent to the Jordan River at an elevation of 330 m below sea level. The site is located on the floor of the Jordan Rift Valley within which lies a thick sequence of lacustrine deposits and associated evaporites, Figure 1.

The tectonic movements which created the Rift Valley are continuing as manifested by the occurrence of modern earthquakes in the region. A wide active fault zone crosses the dam site and underlies the reservoir basin.

A series of confined highly saline aquifers within the Samra formation have been identified at depths in excess of 25 m. Piezometric levels increase with depth such that at 85 m below the damsite the piezometric level is equivalent to future reservoir level and some 30 m above the lowest foundation. An upward migration of saline groundwater through the Lisan Formation therefore occurs naturally at the site.

The unique and particularly adverse geological, hydrogeological and chemical conditions have necessitated a major study of shear strength and related factors influencing stability of the embankment dam.

2 DESCRIPTION OF FOUNDATION SOILS

The Lisan Formation comprises the main sequence of lacustrine deposits which are exposed in the foundations of the Karameh site and are the subject of this paper. This formation at the site has been subdivided, on the basis of lithological characteristics, into the following three distinct units, Table 1 and Figure 1.

The Main Laminated Unit consists primarily of laminated sediments made up of alternating thin to coarse laminae of white aragonite and calcareous silt. In the dam foundations below the water table the material is soft to firm and tight, with gypsum occurring occasionally as a secondary deposit. The laminated silt was found to be particularly sensitive such that it quickly remoulds to a soft putty on working between the fingers.

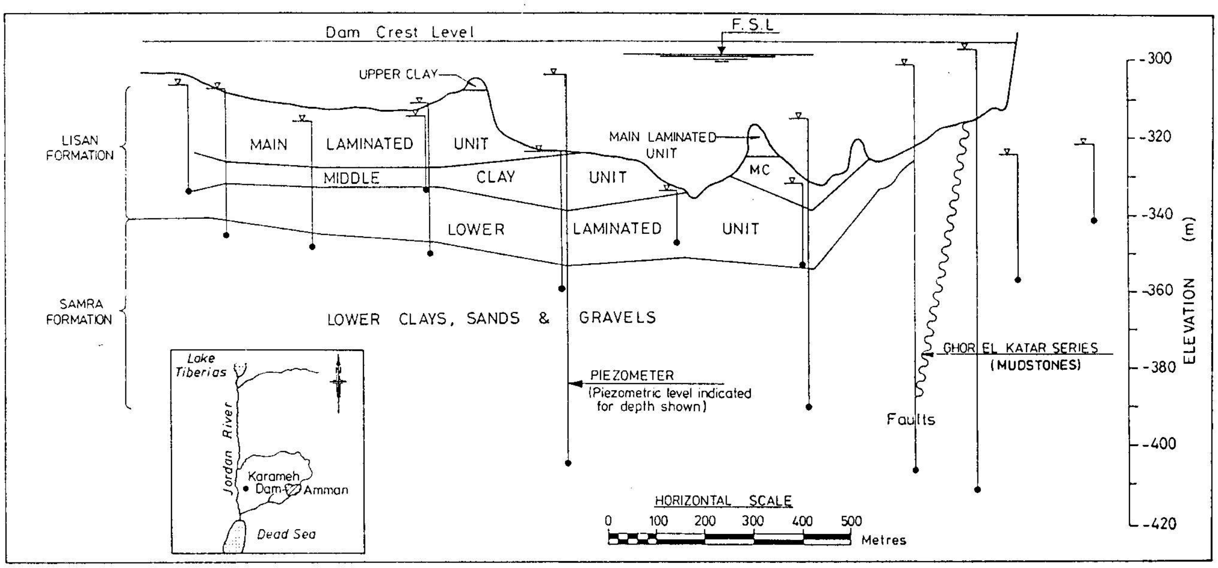

Figure 1 Cross section along dam centreline

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The Middle Clay Unit represents a marked change in the depositional characteristics within former Lake Lisan. The characteristic laminated deposits virtually disappear and are replaced by a sequence of firm clayey silts and calcareous silty clays. Large selenite crystals occur occasionally within the clays.

The Lower Laminated Unit outcrops in the valley bottoms around the site. Laminations are particularly thin and generally of the order of 1.5 mm. Gypsum is found occasionally as thin discontinuous laminae. Secondary gypsum is generally absent.

Table 1. The Lisan Formation

Unit Name	Thickness (Metres)	Unified Soils Classification
Main Laminated (ML)	12 to 15	CL-MH
Middle Clay (MC)	8 to 13	CL-MH
Lower Laminated (LL)	14 to 18	CH-MH

X-ray diffraction and scanning electron microscopy (s.e.m) have shown that calcite is the primary constituent of the clay formations at the site, with quartz as a minor constituent. The soils of the laminated units have alternate white and dark layers and contain more than 80% calcium carbonate. Examinations have shown that the light laminations are rich in aragonite, and that the dark laminations are rich in calcite and quartz and are generally low or lacking in aragonite. The aragonite layers are of inorganic origin and consist of elongated needle-like twinned crystals in which the grains are often arranged in a radial structure. The calcite materials are granular fine grained silts. Diatoms and micro-organisms, often elongated with sieve-like structures, have been identified in samples throughout the formation.

The Lisan deposits are highly overconsolidated and from oedometer tests it appears that the soils have been subjected to a previous overburden pressure of the order of 450 kN/m^2.

3 FACTORS INFLUENCING SOIL STRENGTH

The unique nature of the Lisan soil fabric, the observed sensitivity and the highly saline environment meant that conventional soil behaviour could not be pre-supposed particularly, for long term conditions.

The soils have been found to have a sensitivity, (ratio of undisturbed and remoulded undrained strengths) as high as 6 for the Lower Laminated Unit. Local bedding disturbances within the Lisan soils suggest that historically they may have experienced liquefaction effects. These two factors led to concern regarding the influence of seismic shaking on the dam foundation shear strength. The maximum credible earthquake for the project area has been assessed as Ms = 7.5. A peak ground acceleration recurrence relationship for the project area has been established together with a no damage acceleration (0.2 g) and a maximum rockhead acceleration (0.7 g).

The impounding of a freshwater reservoir in the saline environment could potentially lead to long term chemical changes of the soils following leaching of the saline porewater and dissolution of soluble salts. The salinity of the groundwater generally increases with depth, reaching a mean sodium concentration of 20 parts per thousand at 50 m below ground level.

Pore fluids extracted from the sediments were highly saline but varied in composition. The salinities and magnesium concentrations were sufficiently high for the aragonite to be stable indefinitely in engineering terms. Replacement of the pore fluids by fresh water could potentially lead to the conversion of aragonite to calcite with a consequent change in structure of the soil and hence a possible change in shear strength and other properties.

The radiating crystal structure of the aragonite is to be expected to impart to the soils strengths which are in excess of those which would be normal for materials with such high porosity values and with correspondingly high moisture contents (30 to 70%).

4 TESTING OF SOILS

A wide range of insitu and laboratory tests were carried out. "Special" laboratory testing was used to examine the effects of leaching and dynamic loading on the soils.

4.1 Classification testing

Atterberg tests included the following variations from the standard test. Some similar test variations were used at Sasumua Dam, Terzaghi (1958).

* Distilled water replaced by saline groundwater.

Table 2 Statistical summary of classification test results

Unit Name		Moisture Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Linear Shrinkage (%)	Liquidity Index	Passing 63µm (%)	Passing 2µm (%)	Activity	Specific Gravity
Main Laminates	No. of Results	75	72	72	72	14	72.00	36	35	28.00	29.00
	Mean	42	49	28	22	10	0.37	96	22	2.42	2.73
	Standard Deviation	14	8	6	6	3	0.93	4	16	3.51	0.19
	Max. Value	79	85	54	50	15	2.38	100	53	18.00	3.35
	Min. Value	7	35	18	11	6	-1.78	83	1	0.38	2.45
Middle Clays	No. of Results	71	74	74	74	22	74.00	60	60	56.00	30.00
	Mean	37	56	28	28	12	0.20	94	28	2.67	2.82
	Standard Deviation	8	10	4	8	3	0.62	13	20	4.76	0.30
	Max. Value	54	89	38	52	18	1.91	100	72	30.00	3.48
	Min. Value	8	34	19	11	6	-1.68	28	1	0.33	2.41
Lower Laminates	No. of Results	63	57	57	57	10	57.00	25	25	20.00	11.00
	Mean	51	53	32	22	9	0.03	93	19	3.05	2.78
	Standard Deviation	14	7	5	6	3	1.21	9	14	5.38	0.25
	Max. Value	78	75	41	39	15	1.69	100	50	25.00	3.32
	Min. Value	22	36	18	11	6	-3.00	73	1	0.69	2.44

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* Sample dried at 110°C, reconstituted and immediately tested.
* As above but rehydrated for a period of 28 days.
* Sample thoroughly leached with distilled water.

Moisture contents were determined for a range of temperatures and materials, and particle size analyses were carried out using alternative dispersants.

The results clearly demonstrated that the index properties derived by conventional tests and summarised in Table 2, are unaltered under the influences of fresh-water leaching, drying and hydration time effects. Atterberg limits vary considerably but the mean values for the clay layers and aragonite layers are similar.

The aragonite layers of the laminated soils are 9 - 12% wetter than the clay layers. The differences in the moisture-holding properties of the two layers may be attributed to their different fabric and mineralogy. The bulk moisture contents for the soils of the Lisan members are 20-80% for the laminated members and 20-55% for the clays. Although generally firm insitu the laminated soils have been found to be often close to or even above their liquid limit.

4.2 Undrained shear strength

Insitu shear strength measurements were made using the following tests in parallel at several locations along the dam axis:

* Standard Penetration (SPT)
* Piezocone
* Vane
* Self Boring Pressuremeter
* Flat Plate Dilatometer

Undrained shear strengths deduced from these tests were compared in depth plots, eg Figure 2. The various test methods indicate a large variation in measured strengths, the self boring pressuremeter often giving the highest values.

Undrained shear strengths measured by triaxial testing confirm with some scatter the lower bound values of the SPT and cone testing.

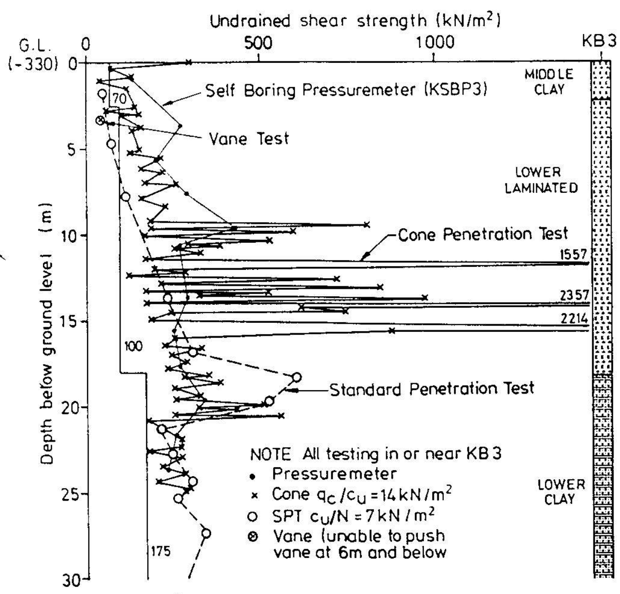

Figure 2 Comparison of insitu undrained strength

4.3 Drained shear strength

Drained shear strength was measured in the laboratory by both triaxial and shear box tests on undisturbed specimens obtained from tube or block samples.

Samples were selected to cover the plasticity range generally associated with the foundation materials encountered on this site. The study showed no large difference in the shear strength as measured with the shear box or in the triaxial apparatus. Results were combined and shown as Mohr circle diagrams or plots of normal stress against shear stress for each of the foundation geological units, eg Figure 3. It is of interest to note that in shear box testing many of the strengths were similar or greater after cycling.

Some samples were leached under a normal stress of 10 kN/m^2 for 14 days in a shear box using distilled water before the shear stage, Torrance (1974). The object of this was to study the effect of dissolution leaching on foundation shear strength. The findings showed no significant difference in drained strength between the leached and unleached samples, Figure 3. X-ray analyses and s.e.m of undisturbed samples before and after extensive leaching showed that all traces of gypsum and sodium chloride had been lost from the samples but no evidence was found of the conversion of aragonite into calcite, thus supporting the findings of the shear box tests. It is of note that a sample which was completely reworked with fresh water showed conversion of 20% of the aragonite into calcite over a period of 8 days.

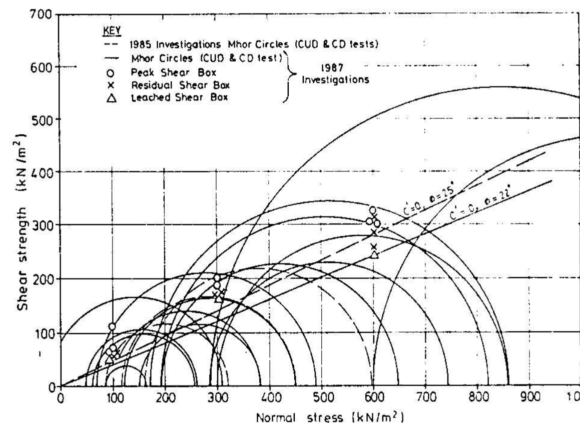

Figure 3 Mohr Circles for effective Stress, Middle Clay

4.4 Dynamic testing

Dynamic loading tests were carried out on representative undisturbed samples of foundation materials to study their performance under seismic loading. The effects on strength and pore pressure were examined in particular.

(a) Shake table tests

These tests were specially developed with Imperial College, London and consisted of exciting samples on a shake table under simulated shallow confinement conditions. Tests were carried out on 300 mm diameter specimens prepared from block samples with laminations horizontal.

Each of five specimens was subjected to both sinusoidal and earthquake motion at the same peak levels. The sinusoidal excitation was for 100 cycles at 3Hz with the "no damage" acceleration (0.2 g). The "no failure" acceleration (0.7 g) and up to 1.4 g were also used; the latter to achieve failure in one of the specimens. The time history used, from Irpina in Southern Italy, corresponds with a magnitude 6.9 event for a soft soil condition giving a peak acceleration of 0.202 g similar to that for Karameh.

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Pore-pressure in the centre of the sample and accelerations at the bottom and top of the specimens were measured, dimensions of the specimens were recorded before and after each test, and quick undrained triaxial tests were carried out on the samples after shaking.

The overall excess pore pressures generated in both the undisturbed and remoulded samples were locally very small and possibly even negative. All samples mobilised strengths large enough to prevent failure during testing under the "no damage" and "no failure" design accelerations.

There was no evidence of distress or failure of samples during and after testing except for one sample of the Main Laminated Unit which was made to fail at 30 Hz by shaking for 30s at 1 g. This sample failed within an aragonite lamination and an examination of the aragonite showed the development of transverse fractures in the crystals. Undrained shear strength testing showed, if anything, a slightly higher strength in those samples subjected to shaking.

(b) Cyclic triaxial tests

Tests were performed on 76 mm nominal diameter specimens at Nottingham University. Pore water pressures, deviator stresses and axial strains were monitored during the tests. After the cyclic triaxial test each specimen was subjected to an undrained compression test to failure. The results, Table 3, indicate that there was no significant pore water pressure rise (ΔP) due to cyclic loading in any of the three foundation geological units. This conclusion accords with the results from the shake table tests.

Table 3 Results of cyclic triaxial testing

Unit	NMC (%)	γ_d (t/m^3)	σ_1	σ_1-σ_3 (kN/m^2)	Cyclic Deviator Min/Max (kN/m^2)	ΔP,1000 cycles (kN/m^2)	Cu (kN/m^2)
ML 1	61	1.03	183	50	0/100	11.8	287
ML 2	66	0.98	400	0	-150/150	15.7	305
MC 1	51	0.91	183	50	0/100	10.4	198
MC 2	48	1.18	400	0	-150/150	0	439
LL 1	37	1.40	183	50	0/100	2.8	522
LL 2	42	1.35	400	0	-150/150	6.8	464
LL 3	40	1.28	412	-115	0/230	6.3	475

σ_1 = Vertical stress; σ_1-σ_3 = Deviator stress
ΔP = Rise in pore pressure after 1000 cycles

5 INTERPRETATION OF SHEAR STRENGTH

In their undisturbed condition the Lisan soils are not prone to the effects of fresh water leaching and it is therefore unnecessary to differentiate between the short and long-term shear strength parameter for the dam foundations. The laminated soils are very sensitive to remoulding, however under cyclic loading it has been demonstrated that no loss of strength occurs. It is possible that the sensitivity is a result of the redistribution of porewater upon physical remoulding of the soil. This strength loss does not occur under dynamic conditions equivalent to seismic loading. No significant build-up of pore pressure in the soils occurs during shaking and accordingly the dynamic pore pressure parameter, A_n Sarma, 1980 has been taken as zero.

5.1 Undrained shear strength

In view of the large variation in strengths and as no relationship whatsoever between moisture content and undisturbed undrained shear strength could be observed, it was considered appropriate to assign to each foundation unit an undrained strength (C_u) based on average laboratory results when considering long failure surfaces, Table 4. Such averages agree well with strengths judged from insitu testing particularly the cone tests. Lower bound parameters have been selected for use locally where soft soils are encountered in the foundations.

5.2 Effective stress parameters

From the results of all effective stress testing the parameters (C', Ø') given in Table 4 were deduced for the various undisturbed foundation units.

The Atterberg limits of each unit are similar. Correlations between the effective stress angle of shearing resistance and plasticity index for normal fine-grained soils are given in NAVFAC DM-7 (1980). Using an upperbound plasticity index of 36%, these correlations suggest a minimum Ø' of 25°. Accordingly dam stability was checked in an alternative simplified analysis with C' = O and Ø' = 25° applied to all saturated Lisan foundation materials.

Table 4. Strength parameters for the Lisan units

Unit	ML	MC	LL
C_u/Lowerbound Cu, (kN/m^2)	55/30	70/30	100/65
C', (kN/m^2)	0	0	0
Ø', (degrees)	27	22	22

6 CONCLUSIONS

The foundation silts and clays of the Lisan Formation consist primarily of aragonite and calcite, often in thin laminations. The aragonite has a structure of long needle-like crystals of high porosity in comparison with the granular calcite material.

The aragonite is potentially liable to conversion to calcite under fresh water leaching. Such conversion has been demonstrated in remoulded laminated soils, but no significant alteration occurs with the intact soils. Shear strengths of the undisturbed foundation soils are unaffected by leaching.

The laminated soils are particularly sensitive to remoulding however there is no loss of undrained shear strength or build-up in porewater pressure during dynamic loading.

Shear strength parameters for undisturbed Lisan soils at Karameh have been proposed.

ACKNOWLEDGEMENTS

Consulting Engineers for the Karameh Project are Sir Alexander Gibb & Partners and Masar Engineering, Amman. Professor N Simons of Surrey University is a special consultant. The Authors thank Mr Zafer Alem, the Director of Dams, Jordan Valley Authority for permission to publish this paper.

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