Fat Clay as a Blanketing Material for Leaky Reservoirs

L'argile grasse comme tapis d'étanchéité de réservoirs à fond perméable

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Summary

The use of fat clay as a blanketing material in leaky reservoirs in limestone areas, has been studied on a large scale in an experimental pond, and in large permeameters in the laboratory.

In the experimental pond, an area of rock with fissures was covered by a rolled layer of fat clay. In one case, failure occurred twice in the form of a hole penetrating this blanket. In other cases, the blanket was successful. Moisture, density, permeability, swelling and pore pressures inside the blanket were measured during the experiments. Methods of protecting the blanket against drying were also studied by the authors.

The experiments were repeated in the laboratory in large permeameters for periods ranging from one to twelve months, up to a maximum head of 6 atmospheres. Each test was carried out until failure occurred, whenever possible.

The authors have described their concept of an "effective blanket", and they have reviewed the practical significance of their tests.

Sommaire

L'emploi d'argile grasse, en tapis d'étanchéité dans des réservoirs en terrain calcaire, a été étudié simultanément à grande échelle dans un petit réservoir expérimental et dans de grands perméamètres au laboratoire.

Dans le réservoir expérimental, un rocher fissuré mis à nu a été recouvert par une couche d'argile grasse compactée. Dans un des cas, le tapis s'est trouvé percé deux fois. Dans les autres cas, le tapis s'est avéré efficace. Des mesures de teneur en eau, densité, perméabilité, gonflement et pression interstitielle ont été faites dans la couche d'argile. On a aussi étudié les moyens d'empêcher la dessication de celle-ci.

Les mêmes expériences ont été répétées au laboratoire dans de grands perméamètres pendant des périodes de un à douze mois et à des charges allant jusqu'à 6 atmosphères. Chaque test a été exécuté jusqu'à rupture quand cela a été possible.

Ces expériences, ainsi que leurs principaux résultats, sont décrits dans ce rapport. On y explique aussi la notion de « tapis effectif » tandis que l'on insiste sur l'importance pratique des essais.

1. Introduction

Conditions for surface water storage in Israel are unfavourable in most cases. The bedrock over large areas of the country is pervious limestone with a depressed groundwater table resulting in excessive seepage losses. Water losses by evaporation are large, due to the arid climate. Since water is scarce and has often to be pumped from a great depth, extreme measures for preventing losses are often justified.

The method of clay blanketing, for reducing seepage losses, has been applied to some reservoirs. In the Beit Netofa valley — a karstic area in Galilee — where a large storage reservoir was contemplated, blanketing tests were carried out in an experimental pond. The purpose of the investigations was to discover the optimum design requirements as to the minimum thickness of the blanket, placing conditions and subsequent performance. Similarly parallel tests were also performed in large permeameters in the laboratory.

The authors give the results and conclusions of the investigations in their present stage. Several aspects of the problem such as wave erosion and stability on slopes will have to be investigated later on.

2. Clay blanketing tests in experimental pond

(a) *Test pond 'B'* :

The pond constructed in 1954 has a rectangular shape confined by a fat clay dyke built on a hill slope and consolidated by rolling. It is 8·0 m high at its maximum cross section with a total length of 240 m. The total capacity at flowline is 13·000 cub. m with 4 530 sq. m of water covered area. The average water head (at flowline) in the northern part is 2·85 m increasing to 5·15 m at the southern end.

The pond floor, consisting of Eocene chalky and flinty pervious limestone, covers 1900 sq. m. The water table is about 15 m below ground level.

(b) *Seepage Tests Before Blanketing* :

The first filling period (9-2-55 — 28-2-55) started with initial losses of 1·76 meters per day. Losses later ranged between 0·86 — 1·88 meters/day with an average head of 0·20 — 1·65 meters.

Initial losses during the second filling period (18-5-55 — 5-6-55) were at a rate of 2·20 meters. With different water heads of 0·35 — 3·58 m, losses were between 1·21 — 3·57 meters per day.

(c) *Blanketing with 0·55 m rolled fat clay* :

Following the seepage tests on the rock bottom, the floor was stripped of roots and vegetation. In some places rock had to be blasted in order to obtain a regular slope of about 6 per cent. A few depressions, mainly near the southern dyke, covering an area of about 300 sq. m, were filled with rubble and crushed stone to a maximum thickness of about 0·30 m (Photos no 1 and 2).

Construction of 0·55 m average thickness of blanket took place in August 1955. It was built of rolled highly plastic, montmorillonite fat clays (Liquid Limit 78, Plastic Limit 31). The maximum Proctor density varied between 1380-1450 kg cub. m and the optimum moisture content between 31 per cent — 28 per cent respectively. The blanket was constructed in four layers rolled by a twin sheepfoot roller in 12 to 14 passes, exerting a pressure on the ground of from 30 to 35 kg per sq. cm.

In October 1955 the pond was filled to flowline elevation. During October and November, the average seepage losses ranged from 4·2 — 6·7 millimeters per day. On 16th December the average water drop suddenly increased to 44·6 millimeters/day. After letting out water from the pond, the blanket was found to have been pierced by a cylindrical hole (20 cm in diameter) near the southern dyke, where the blanket had been constructed on rubble and crushed stone filling.

Photo 1 Pond '*B*' (clay blanket and measuring devices).
Réservoir '*B*' (tapis d'argile et appareils de mesures).

The test was repeated after the hole had been sealed. Since there was likelihood of another hole being formed, the pond was filled during March to an elevation sufficient to maintain the whole blanket under water (average water head : south 2·44 meters, north 0·14 meters). The average seepage losses during March were 0·5 millimeter per day tending to show an increase to 1·2 millimeter/day towards the first week in April. When the water level was brought up again to flowline elevation, the average seepage losses increased to 21·0 — 22·4 millimeters per day. On 2nd May 1956 the pond was emptied, and a fresh hole was discovered near the southern dyke where the blanket had been placed on rubble and crushed stone.

Photo 2 Pond '*B*' (general view).
Réservoir '*B*' (vue générale).

(d.) *Blanketing with Rolled clay :*

At the end of the summer of 1956, a new rolled clay blanket was constructed in pond '*B*' — with an average thickness of 1·10 m — after the old blanket and the rubble filling had been completely removed from depressions in the floor. Clay materials and placing conditions were similar to the previous test with 0·55 m clay blanket. The blanket was constructed in nine layers.

The new blanket was put under full water head until July 1958 when the pond was emptied. During a test period of 19 months no failure occured in the blanket. The seepage rate was of the order 0·3 — 1·7 millimeter per day. The average daily seepage rate for 308 measuring days has been 0·74 millimeters.

(e) *Removal of* 0·5 *m Blanket :*

In September 1958, about 0·5 meter of the existing 1·10 meter blanket was removed in order to test it against failure with no rubble filling between the rock surface and the clay blanket. Since October 1958 the blanket has been under full water head. The seepage rate during the following height months was of the order of the order of 0·6 — 1·5 millimeter.

In June 1959 the pond was emptied and the blanket was exposed to drying conditions. After five months exposure, during which cracks and changes in moisture content occured only in the top 20 cm the pond was refilled in December 1959. Up to the end of June 1960 the blanket remained intact, with no changes in the seepage rate.

During all the above tests, the following measurements were carried out : moisture, density, pore pressure and swelling (see Tables 1, 2 and Fig. 1).

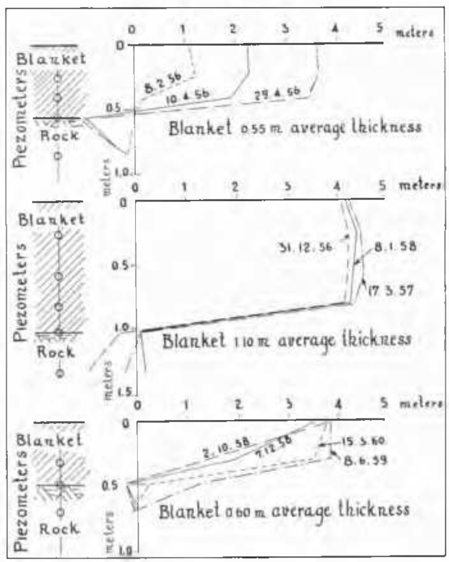

Fig. 1 Pond '*B*'. Head diagrams in blanket.
Réservoir '*B*'. Diagrammes des charges hydrauliques dans le tapis.

3. Test area for different protective cover of clay blankets

(a) *Description of the Test Area :*

A separate Test Area (20 × 20 m) was constructed near pond '*B*'. The horizontal rolled clay blanket confined by a rolled embankment was built on a sloping rock. It varied in thickness from 0·25 m in the north to 1·75 m in the south.

Table 1

Tests in pond 'B'

Essais dans le réservoir 'B'

Before testing					*After testing*				
Depth from top cm	*Dry density and moisture content* *Maximum* kg/m³		*Maximum* kg/m³		*Depth from top* cm	*Dry density and moisture content* *Maximum* kg/m³		*Minimum* kg/m³	
				0·55 m CLAY BLANKET					
0-15	1 390	28·3 per cent	1 193	19·6 per cent	0-20	1 176	43·2 per cent	1 101	49·0 per cent
15-30	1 432	22·2 —	1 245	33·3 —					
30-45	1 418	25·7 —	1 233	31·4 —	20-40	1 215	40 —	1 118	47·5 —
45-55	1 431	28·2 —	1 192	31·0 —					
				1·10 m CLAY BLANKET					
					0-5		63·4 —		
0-16	1 497	22·4 —	1 324	24·7 —	5-20	1 023	37·1 —	1 001	42·2 —
16-28	1 462	21·6 —	1 318	27·7 —					
28-40	1 516	21·2 —	1 263	28·2 —	20-35	1 133	41·0 —	1 035	42·0 —
40-52	1 447	26·7 —	1 275	35·1 —	37-52	1 187	38·0 —	1 130	36·4 —
52-64	1 448	27·0 —	1 218	31·3 —	52-67	1 233	35·2 —	1 174	35·3 —
64-76	1 460	26·5 —	1 219	26·8 —	67-80	1 231	34·3 —	1 217	33·1 —
76-88	1 466	24·6 —	1 182	31·4 —					
88-100	1 423	22·5 —	1 278	34·6 —	85-100	1 190	46·5 —		
100-100	1 441	32·0 —	1 313	38·1 —					
				Removal of 0·50 m BLANKET					
					5-17	1 275	37·1 —	1 155	35·0 —
					21-33	1 372	34·1 —	1 370	34·7 —
					35-47	1 322	35·0 —	1 295	35·8 —
					51-63	1 295	33·0 —	1 260	32·2 —

Table 2

Swelling measurements in pond '*B*'

Essais de gonflement dans le réservoir '*B*'

Depth of measuring plates from top in cm	*Rise of measuring plates in* cm *(during testing)*
0·55 m CLAY BLANKET	
10	5·8
10	6·3
10	6·8
10	7·4
32	2·5
32	3·0
32	2·2
32	2·0

Depth of measuring plates from top in cm	*Rise of measuring plates in* cm *(after testing)*
1·10 cm CLAY BLANKET	
5	9·9
5	8·2
30	6·2
30	4·7
40	1·5
50	1·4
65	1·3
67	0·2
81	0·3
93	0·0

The blanket was constructed from similar materials and under identical, placing conditions with those used in pond '*B*'.

(b) *Test procedure :*

The test area was divided into six plots (20·0 × 3·3 m).

Plot No. :

1 : Quarry run 0·50 m in thickness.

2 : Riprap 0·30 m in thickness overlying 0·20 m of filter materials.

3 : Loose soil 0·30 m in thickness.

4 : Loose soil 0·10 m in thickness mixed with 2·5 kg Krilium per cubic meter of loose soil.

5 : No protective cover has been provided.

6 : An asphalt (40/50) membrane 0·4 cm in thickness.

The test area was kept covered with water from October 1955 until May 1956. Since then, it has been exposed to drying conditions during the summer months and flooded again during the rainy season, until October 1958.

(c) *Results :*

Moisture contents were determined to a depth of 1·50 m at various periods. Initial figures were around 37·5 per cent. In plots 5 and 6 a gradual drying and cracking was observed to 0·50 — 0·60 m depth. Moisture content remained fairly constant (30 per cent — 32 per cent) to a depth of 1·50 m. In plots 3 and 4 drying and cracking developed to a depth of 0·60 — 0·70 m with thick growth of vegetation. Moisture remained constant (30 per cent) over a depth ranging from 0·20 to 1·50 m.

In plots 1 and 2 cracks developed to depths of 0·20 and 0·05 m respectively. Moisture remained constant below 0·90 and 0·30 m, (34 per cent — 35 per cent) respectively.

4. Tests in large permeameters

(a) *Description of Permeameters :*

The purpose of the laboratory clay blanketing tests was to reproduce conditions as closely as possible to those prevailing in pond '*B*'.

During 1957/58 four large permeameters were constructed at the Tahal Soil Laboratory, Haifa. The permeameters consisted of two 1·20 m steel cylinder 0·58 m in diameter, each with 10 connections for piezometer cells and 10 atmosphere gauges. The convex top covers were provided with three openings for direct swelling measurements. Both permeameters were connected to the main through reduction valves and control manometers. (Photo No. 3.)

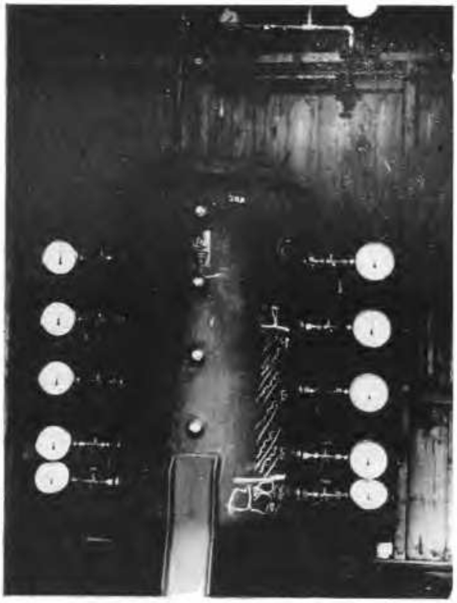

Photo 3 Large permeameters (general view).
Grands perméamètres (vue générale).

(b) *Test Procedure :*

Six permeability tests with Beit Netofa fat clay (Nos. 1, 2, 3, 4, 5, 6) remoulded samples 0·50 — 0·55 m thick underlain by 0·12 m layer of rubble (0·10 — 0·20 m) and crushed stones. One sample (test No. 5) was tested with 0·10 m of coarse and fine gravel filter.

Test No. 10 was performed with 0·10 m Beit Netofa clay, underlain by 0·15 m filter material and 0·47 m cover of fine to medium sand.

It had been intended to test clay samples with a dry density of about 1 380 kg per cub. m, varying in moisture content from 25 per cent to 35 per cent, i.e. 5 per cent on the dry and wet side of the optimum moisture content. The clay materials passing No. 4 sieve, were compacted to the required densities in layers from 5 to 10 cm thick.

Some results are presented in Table No. 3, Fig. 2 and photo No. 4.

Photo 4 Large permeameters (failure).
Grands perméamètres (renard).

5. Discussion of results

(a) *Variation of the hydraulic gradient within the blanket.*

The head diagrams, deduced from the measurements in piezometers, at various depths, in the pond as well as in the permeameters, show the same picture : a very low hydraulic gradient in the upper part of the blanket, while in the lower part the gradient may reach very high values up to 300. This means that during flow the permeability has become much higher in the upper part of the blanket. This difference in the rate of permeability is probably due to a decrease of swelling with depth.

If effective pressure diagrams are plotted for flows under various heads, it is seen that at the bottom of the blanket, where the pressure is equal to one atmosphere, the effective pressure is much higher than in the hydrostatic state due to the seepage pressure. The pore pressure diagram, deduced from measurements in the piezometers, is nearly vertical at its upper part and very flat at its lower part (Fig. 3). The effective pressure, at a depth z, is equal to :

$$p = (h_0\gamma_w + z\gamma) - u$$

where :

h_0 = Water head above the blanket
γ_w = Density of water
γ = Density of the saturated soil
u = Pore pressure

Theoretically, for a given head of water, the value of the swelling pressure and the relationship between swelling or consolidation and effective pressure, will determine the degree of swelling or consolidation at each depth in the blanket. The lower 25 — 30 cm of the blanket, where both effective pressure and hydraulic gradient are high, may be called the "effective blanket" because this part takes most of the seepage forces.

Table 3

Tests in Large Permeameters

Essais dans les grands permeametres

Clay	72 per cent	*L. L.*	87·5 per cent	Opt. moisture	28·4 per cent
Silt	21 —	*P. L.*	31·5 —	Max. density	1 420 kg/m^3
Sand	5 —			Specific gravity	2·75
Gravel	2 —				

	Before testing				*After testing*			
	Test No. 1	*Test No. 3*	*Test No. 5*	*Test No. 10*	*Test No. 1*	*Test No. 3*	*Test No. 5*	*Test No. 10*
	Samples on the dry side of optimum							
Av. dry density kg/m^3	1 382	1 378	1 383	1 392	1 133	1 144	1 226	—
Av. moisture content (per cent)	24·9	26·0	25·0	26·3	42·7	42·0	46·7	—
Moisture content at saturation (per cent)					52·4	51·0	47·0	
Thickness of sample in cm	55·4	55·1	55·1	9·8	60·8	61·5	61·6	10·6
Total Swelling (per cent)					9·8	11·6	11·8	6·1
Duration of test in days					40	251	335	140
Number of days required for the passage of water					40	64	50	14
k in cm/sec (gradients 22-300)						$3 - 9 \times 10^{-8}$	$1 \times 10^{-7} - 5 \times 10^{-8}$	$1 - 2 \times 10^{-7}$
Gradient at failure of sample					22	76	no failure gradient 112	no failure gradient 300

	Before testing			*After testing*		
	Test No. 2	*Test No. 4*	*Test No. 6*	*Test No. 2*	*Test No. 4*	*Test No. 6*
	Samples on the wet side of optimum					
Av. dry density kg/m^3	1 374	1 358	1 363	1 185	1 226	1 308
Av. moisture content	33·7	35·1	33·5	40·7	41·3	44·1
Moisture content at saturation (per cent)				47·8	45·2	40·0
Thickness of sample in cm	55·1	55·4	49·9	59·9	58·6	52·7
Total Swelling (per cent)				8·7	5·8	5·7
Duration of test in days				169	320	166
Number of days required for the passage of water				49	101	131
k in cm/sec (gradients 24-112)				$4 \times 10^{-8} - 2 \times 10^{-7}$	$1 - 4 \times 10^{-9}$	4×10^{-9}
Gradient at failure of sample				58	112	24

(b) *Swelling rate :*

Swelling occurs very rapidly before the water has seeped through the blanket. It appears that "dry" compacted samples swell from 2 per cent to 3 per cent more than "wet" ones, which conforms with experiments described in ref. [5]. The "dry" samples are less dispersed than the "wet" ones. Values of swelling seem to be larger in the pond than in the large permeameters. This may be due to differences in the degree of saturation or of the placing conditions, leading to a variation in the constituency of the clay.

It would seem that swelling at various depths can be deduced from the moisture and density figures determined after completion of each test. Actually these figures have only an indicative value, since, after the test, the hydrostatic state has been re-established and some swelling may have taken place. Furthermore, after the drainage which follows the test, some consolidation may occur at the top.

These figures tend to show that the degree of saturation is only 80 per cent — 100 per cent. The actual figures should probably be higher and saturation nearly complete.

(c) *Failure of the Blanket :*

The failure, which closely resembles the formation of holes in karstic regions, has the following characteristic features : It starts from the bottom of the blanket upwards, occurring only when the layer below has large voids (10 mm at least); Usually it takes some time (a few weeks) before it develops.

The main cause of this failure is very probably due to seepage pressure resulting from the high hydraulic gradient

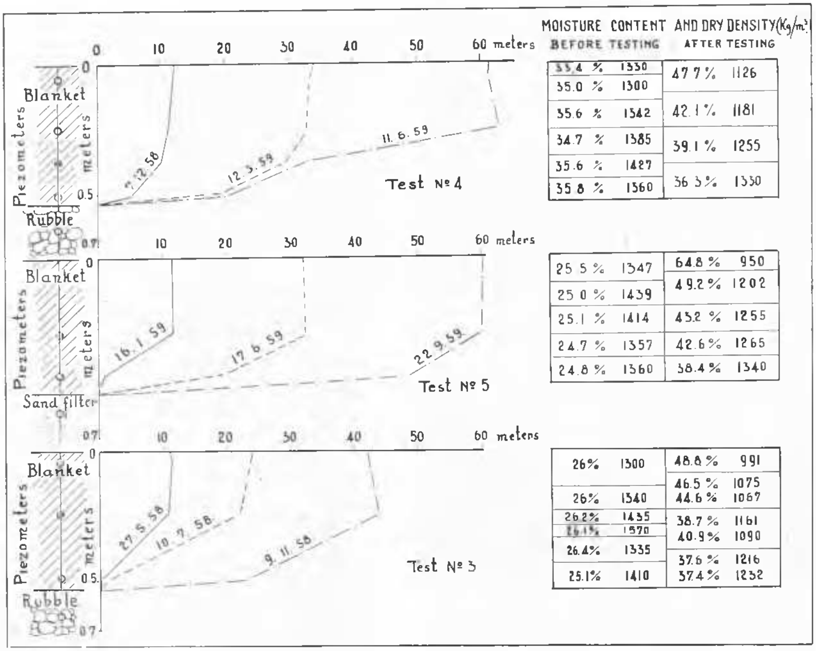

Fig. 2 Large permeameters. Head diagrams in blanket.
Grands perméamètres. Diagramme des charges hydrauliques dans le tapis.

above the voids. The high seepage pressure entrains the clay particles into the large voids. Then thin layers are gradually removed off until the "effective blanket" has been pierced. Once in the weaker swelling zone, piping takes place very rapidly and failure occurs.

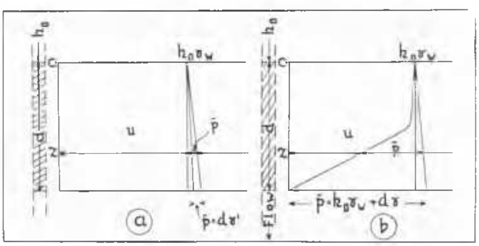

Fig. 3 Pore-pressure u and effective pressure p shown in schematic diagrams, when a blanket is under water head h_0. (a) Hydrostatic state; (b) State of flow.
Diagrammes schématiques de la pression interstitielle u et de la pression effective p lorsque le tapis se trouve sous une pression h_0. (a) Etat hydrostatique ; (b) Etat d'écoulement.

It is to be expected that the more cohesive the clay, the larger will be the resistance to piping, but experiments did not reveal any clear difference between "dry" and "wet" compacted samples.

The resistance to piping will continue to decrease if swelling is allowed to reach the bottom of the blanket. The fact that piping has occurred at lower heads in the pond than in the permeameters, can probably be explained by the more regular conditions of placing in the laboratory.

(d) *Negative pore pressures :*

In some tests small negative pressures have been measured at the bottom of the blanket. They may be infered from the shape of the head diagram. These negative values seem to disappear with time and are probably caused by incomplete saturation of the lower part of the clay, itself due to an incomplete expulsion of air.

(e) *Permeability coefficients :*

Permeability coefficients are of the same order of magnitude in the large permeameters ($k = 10^{-7} — 10^{-8}$ cm/sec). However, they seem to be larger in the "dry" compacted samples than in the "wet" ones. This may be explained by the difference in structure, the dispersion being larger in the "wet" samples.

The permeability of the blanket in the pond is definitely larger than in the permeameters ($k = 10^{-6}$ cm/sec), which may also be explained by the smaller degree of dispersion in the clay and less regular placing conditions.

6. Conclusions

(a) A rolled fat clay blanket constructed on a leaky reservoir may have a permeability of less than 1 millimeter per day.

(b) Failure of the blanket by piping (blow hole) may occur if large voids (above 10 millimeters) are left directly under the blanket. In such a case it may be essential to insert an intermediate material below the blanket.

(c) A protective cover on the blanket is required to prevent drying and in order to keep a minimum effective load against excessive swelling. A layer of about 0·50 m of quarry run may be satisfactory.

(d) The thickness of the blanket itself may be quite small if sufficiently loaded. A layer of 0·50 m rolled fat clay, of the type described above seems to be adequate for shallow reservoirs.

(e) The blanket, compacted "wet", seems to be more impervious and less susceptible to swelling than one compacted "dry", although the latter might have the advantage of higher strength and better workability during construction.

(f) Large permeameters seem to be suitable for the study of the engineering properties of clay blanketing materials. but tests of long duration are necessary.

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