FAULT MOVEMENT: ITS POTENTIAL DAMAGE TO EMBANKMENT DAMS

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SUMMARY

This paper describes in detail a preliminary centrifuge model study to investigate possible damage and rupture of a homogeneous embankment dam due to fault movement. The results indicate that the crest displacement can be related to basement fault movement and, furthermore, the crest length is an important variable to be considered in scale modeling as it may affect the type of failure mechanism experienced by a dam. The results further demonstrated the feasibility of using centrifuge models to study dam behavior and point to the need for larger models to be tested in a large centrifuge.

INTRODUCTION

One of the continuing problems confronting the geotechnical and structural engineers is the lack of a procedure for assessing, rationally, the danger of damage to dams located across active faults. Fault displacements of large magnitudes can cause abrupt surface rupture of a few feet to tens of feet, hence the assumption of a continuum customarily made in analyzing the stress, strain and deformation in an earth structure is not accurate. Similarly, conventional design guidelines do not address the problem of fault movement because of the lack of available relevent information.

Based upon the findings of a comprehensive field and literature surveys, Sherard, Cluff and Allen (Ref. 1) argue: "... There have been essentially no failures or damage to dams caused by displacements of faults during earthquakes. While fault displacements during earthquakes are spectacular events which would seriously damage a dam, they have been so rare that the coincidence of a large offset passing through a dam foundation has not yet taken place." Therefore, they concluded among other observations that: "We are confident that conservatively designed embankment dams will withstand without failure the worst conceivable damage imposed by foundation fault movements... provided that there are materials available from which to construct thick, protective zones of cohesionless transition materials."

It can be seen that, to date, this aspect of dam design is largely empirical, stressing the importance of a proper choice of design details, such as a transition zone, to ensure safety against rupture or breakage. The guidelines suggested are based upon related field performances of a limited number of dams subjected to fault movement in the foundation and upon the judgment of experienced dam designers. Little of this information, however, can be quantified to form the basis of a general and yet practical procedure for evaluating the safety of existing or proposed embankment dams.

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Table 1 is a partial list, compiled by Bennett (Ref. 2), of embankment dams in California located on active faults. Some of them are situated precariously above densely populated areas. Should a dam fail, due to fault movements, the consequences of potential damage are awesome. Furthermore, in the future new dams may be built over faults. Therefore, there is a need for new approaches that will shed light on this problem. One of the possible approaches is the use of a centrifuge model study of dam structures.

TABLE I

EMBANKMENT DAMS IN CALIFORNIA LOCATED ON ACTIVE FAULTS — A PARTIAL LIST

Dam Name	Height of Dam (ft)	Crest Width (ft)	Total Free-board (ft)	Type of Dam	Storage Capacity (acre-ft)	Volume of Dam cu. yd	Year Com-pleted	County	Fault	M.C.E.	Max. Disp. (ft)	Remark
Lake Ranch Dam	38	20	4.5	ERTH	337	5,000	1877	Santa Clara	San Andreas	8.5	20	Outlet broke during 1906 EQ. dam failed partially.
San Andreas Dam	107	20	10.0	ERTH	18,500	540,000	1870	San Mateo	San Andreas	8.5	20	1906 break cuts hill between dam & spillway.
Coyote Dam	140	100	26.0	ERRK	24,500	1,130,000	1936	Santa Clara	Calaveras	7.5	15	Some anti-fault features built into the design.
Quail Lake	45	22	2.0		5,600	1,360,000	1967	Los Angeles	San Andreas	8.5	20	Not a jurisdictional dam on California Aqueduct.
Cedar Springs	236	42	23.0	ROCK	78,000	7,900,000	1971	San Bernadino	Cleghorn	6.5	3	Some anti-fault features built in design.
Calaveras Dam	210	30	22.4	ERRK	100,000	3,461,000	1925	Alameda	Calaveras	7.5	15	Fault near dam only.
Lower Howell Dam	39	18	3.9	ERTH	153	29,600	1877	Santa Clara	San Andreas	8.5	20	
Upper Howel Dam	36	20	4.5	ERTH	243	31,460	1878	Santa Clara	San Andreas	8.5	20	
Lake Temescal	116	40	14.5	ERTH	435	262,292	1869	Alameda	Hayward	7.5	15	
Grant Co. #2 Dam	27	12	4.0	ERTH	600	16,050	1927	Santa Clara	Calaveras	7.5	15	
Harold Dam	30	10	11.5	ERTH	4,200		1891	Los Angeles	San Andreas	8.5	20	
Hensnavy Dam	123	20	13.0	HYDE	203,531	500,000	1923	San Diego	Elsinore	7.5	7	Downstream buttress designed for fault offset.

ERTH = Earth Fill Dam, ERRK = Earth and Rock Fill Dam, ROCK = Rock Fill Dam, HYDE = Hydraulic Fill Dam, M.C.E. = Max. Credible Earthquake Magnitude.

CENTRIFUGE MODELING OF AN EMBANKMENT DAM

The centrifuge available at UC Davis is a one-meter radius Schaevitz B-8-D rotary accelerator capable of operating at a capacity of 10,000 g-lbs. (e.g., 100 lbs. at 100 g's). The dimensions of the bottom of the swing platform are 17 in. by 17 in., thus the size of the embankment model to fit the platform is limited. There are, however, many factors which seriously affect the stability of an embankment dam following a fault displacement, namely, transition zone, fault displacement and type, shape of valley, reservoir water level, foundation type, type of embankment, and others. It is impossible to properly simulate in a small model all these details and to observe the interplay of many factors. Only a limited scope is chosen for this preliminary study with the following objectives: 1) to evaluate the feasibility of centrifuge modeling of dam breakage due to fault displacement; 2) to observe and to understand the damage patterns in an embankment dam of simple design; and 3) to demonstrate the need for a large size centrifuge for detailed studies.

The Model

The model box is made of aluminum; inside, there are two basement rock and abutment model elements lying on either side of the fault line, made of wood. One side of the basement and abutment is fixed to the aluminum box; however, the other side can be moved in a simple strike-slip movement by an air piston positioned in the basement rock. The piston is connected to a high pressure (600 psi) cylinder mounted near the center of the centrifuge arm. The movement of the piston can be adjusted to produce a horizontal displacement of the sliding block in the range of 0.1 in. to 0.5 in. This movement is applied suddenly under the control of an electrically triggered solinoid valve. A picture of the test set-up with an actual model is shown in Figure 1. Grooves are cut in the wooden abutment blocks to prevent possible slippage between soil and model rock at the interface. As the problem of water leakage through the fault line cannot be eliminated at this time, tests are conducted without an impounding reservoir behind the dam.

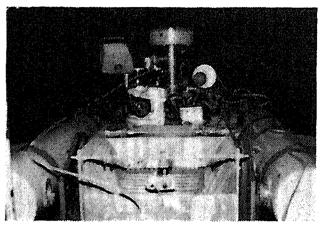
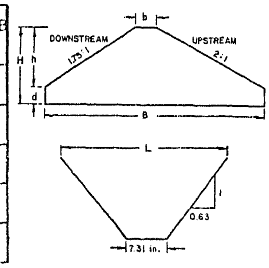


FIGURE 1. MODEL AND CENTRIFUGE ARRANGEMENT

TABLE 2

MODEL AND PROTOTYPE DIMENSIONS

	Prototype	Group A (60-g)	Group B (80-g)
h	18'	3.6"	2.7"
d	4.5	0.9	0.68
b	5	1	0.75
B	72.5	14.5	10.88
L	60/72	11.83	10.79



The Testing Program

Because of the size of the swing platform and the capacity of the UCD Schaevitz centrifuge, only simple models and relatively few parameters are studied. Accordingly, the details of the testing program are described as follows:

1) Model dams are built of compacted yolo loam of homogeneous cross section. The placement water content and dry density are 17% and 110 lb./ft.^{3} respectively. The embankment is compacted in lifts of approximately 0.9 in. thick. The compacted model is cured in the moisture room overnight prior to testing.

2) Model dams are built to simulate an 18 ft. high prototype dam. The upstream and downstream slope are 1:2 and 1:1.75 respectively. The base of the dam is 72.5 ft. wide. A 4.5 ft. thick alluvial deposit of yolo loam covers the valley floor and serves as the foundation of the dam. Two groups of models are tested under two different g-levels, their corresponding cross-section dimensions to properly scale the prototype size are given in Table 2. It should be noted that the shape of the valley and the dimensions of the abutment blocks in the model box are not altered for the different model groups, therefore, the crest length to dam height ratio of the two groups are different.

3) An LVDT positioned at the crest line one inch from the fault on the moving block is used to monitor the model response to a sudden displacement. Furthermore, white paint lines parallel to the crest

are drawn on the downstream surface of the embankment; a line of white-head pins are also placed along the centerline of the dam crest. These markers give a visual display of the movement of the dam for still photos and T.V. viewing while testing is in progress.

4) A total of eight tests were performed which was divided into two groups of four each. Group A models were tested at 60 g's, whereas the Group B models were smaller in size and tested at 80 g's. The amount of basement displacement varied from model to model.

5) To start the test, a model was first brought to the proper g-level under which the basement displacement was to be applied. The model was then kept at that g-level for 10 minutes. During that period, the LVDT reading was monitored to check if the dam is "stable" under that g-level. A sudden horizontal displacement at the basement rock was applied; the crest movement was recorded and several still photos were taken for the next 15 minutes before the test was terminated.

Results

Results from the eight tests are tabulated as shown in Table 3. Furthermore, the results are plotted in Figure 2 showing the relationships between the basement rock displacement and the corresponding crest displacement for both groups of models. A number of observations of the test results are given below:

TABLE 3

RESULTS OF BASE ROCK DISPLACEMENT

Group	Test No.	Base Displ. δ_b(in)	Crest Displ. δ_c(in)	H (in)	δ_b/H	δ_c/H
A	1	0.30	0.065	4.5	0.067	0.014
	2	0.25	0.050	4.5	0.056	0.011
	3	0.40	0.150	4.5	0.089	0.033
	4	0.10	0	4.5	0.022	0.000
B	5	0.30	0.164	3.375	0.089	0.047
	6	0.25	0.120	3.375	0.074	0.036
	7	0.10	0.060	3.375	0.030	0.018
	8	0.16	0.095	3.375	0.047	0.028

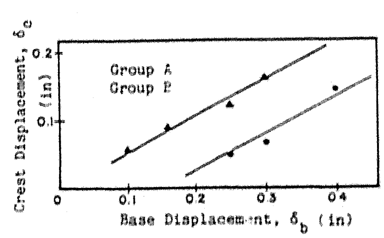


FIGURE 2. BASE ROCK VS. CREST DISPLACEMENT

1) Cracks developed immediately after the basement rock is moved; no further movement of the crest nor the openings of cracks were noticed during the additional 15-minute run.

2) For a given group of models, the amount of crest movement can be related to the basement rock movement.

3) The crack patterns are different for the two groups of models. Group A shows a more or less 45° crack pattern (Figure 3), while Group B, on the other hand, has basically 90° cracks parallel to and located relatively closely to the fault line (Figure 4).

4) For the same amount of basement movement, a Group B model experiences a larger crest movement than the corresponding Group A model.

5) The crack openings in the embankment are larger near the base of the dam. When the basement displacement is relatively small, the crack may not reach the crest of the dam.

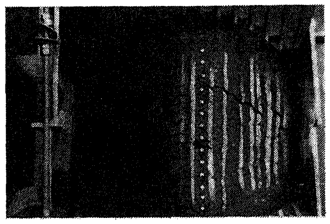


FIGURE 3. CRACK PATTERNS IN GROUP A TESTS

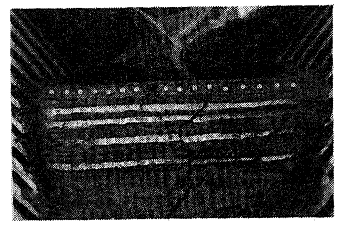


FIGURE 4. CRACK PATTERNS IN GROUP B TESTS

INTERPRETATION OF RESULTS

The results recorded in Table 3 can be used to test the range of consistent results for physical modeling (modeling of models) over a range of scales of the parameters studied. In the case of this project, the parameters studied are those related to the cross-section of a homogeneous compacted earth dam placed on an alluvial deposit.

It can be seen that two almost parallel lines can be drawn through the data points and each line represents a different L/B ratio. The results seem to indicate that for the range of δ_b studied, a linear relationship between the fault displacement and the crest movement exists for a given L/B ratio. This demonstrates that the crest movement is effected by the L/B ratio in the model, therefore, for proper modeling, the crest length must also be scaled.

By examining the crack patterns shown in Figures 3 and 4, one could conclude that two different rupture mechanisms may be responsible for the difference. It may further be suggested that since the L/B ratio of the two groups was not the same, the rupture mechanism may be related to the L/B ratio of the model dams. The crack pattern in Group A models runs approximately at 45° to the fault line, and appears mostly in zones where displacement induced tension is expected. This type of crack pattern is consistent with diagonal tensile strains at approximately 45° with respect to the shear plane seen in Figure 3. These tension cracks are not continuous from one surface of the embankment to the other. The Group B models failed by rupture planes cutting across the dam, parallel to the fault line. Conceivably the probability of water leakage and severe erosion which could trigger the collapse of dam is much higher for cracks obtained in the Group B models, because the cracks are continuous. Of course, continuous tensile cracks across the embankment dam would be more critical. This conjecture will be evaluated in future tests, along with the influence of transition zones in embankment dams on the ability to seal or to minimize leakage after cracking.

The mode of failure across the dam, whether transverse shear cracks or diagonal tensile cracks may depend upon the initial state of stress in the dam. Compaction of the material between relatively close abutments (small L/H) could result in lateral stresses above the at-rest lateral stress condition. The relatively longer dam (larger L/H), although still likely to have lateral stresses greater than the at-rest state, might be likely to have stresses lower than those obtained in the narrow abutment case.

The base rock relative displacement forces a shear deformation on the dam to the point of rupture. The shear deformation gives rise to stresses which will cause rupture of the soil body as they reach limit states. Limit states may be reached either in shear stress or in tensile stress. The limit states in shear are dependent upon the normal stress on the shear plane or the confining pressure.

Because the upstream and downstream faces of the dam are stress-free, the shear force on the abutments must be accompanied by moments produced by normal force distributions σ_B, shown in Figure 5a. In construction of the dam, lateral stress σ_o may be generated due to compaction. The combined stress is then $\sigma = \sigma_o + \sigma_B$.

An element, A, in the dam near the abutment may have stresses in tension in one direction combined with shear as shown in Figure 5d. The tensile stress shifts the Mohrs circle of stresses so that a tensile limit may be reached before the Mohr-Coulomb shear limit as shown in Figure 5d.

On an element B on the mid-cross section of the dam, the σ_B stresses are zero, and the normal stress reduces to σ_o as shown in Figure 5c. The center of the Mohrs circle of stress is shifted away from the tensile limit and, therefore, may lead to failure on the Mohr-Coulomb line as shown in Figure 5d.

The values of σ_o and σ_B must be small with respect to τ, in order that failure planes stand roughly at 45° to the fault line in Group A and parallel to the fault line for Group B.

In the models constructed in the test program, the actual determination of initial stress state in the embankment was not determined, hence the results can only be related by ratios of the dimensions. Also, due to the complex geometry of the dam, stress distributions owing to the fault movement will be different than the simple distribution used above for discussion. Interpretation of the results empirically must involve the base fault motion δ_B, the crest movement δ_C, the height H, width B and length L of the embankment dam. Two non-dimensional parameters have been observed that greatly reduces the spread in the data. The ratio $(\delta_B - \delta_C)/H$ is a measure of internal shear strain between top and bottom of the dam, and $\frac{\delta_B B}{L^2}$ represents a measure of base shear strain modified by the width to length ratio. The data are shown in Figure 6 plotted with respect to these two non-dimensional parameters.

One can still detect a slight difference between Group A and Group B data in Figure 6, although small. This fact and the realization that the failure mechanisms are different between the two groups should make one cautious until much more data is obtained.

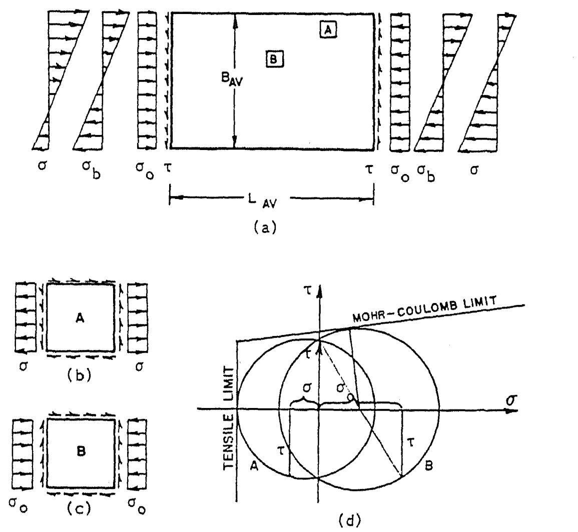


FIGURE 5. (a) STRESS DISTRIBUTION ARISING FROM ABUTMENT RELATIVE DISPLACEMENT, (b) INTERNAL STRESS NEAR ABUTMENT IN TENSION ZONE, (c) INTERNAL STRESS AT CENTER, (d) TWO FAILURE STATES

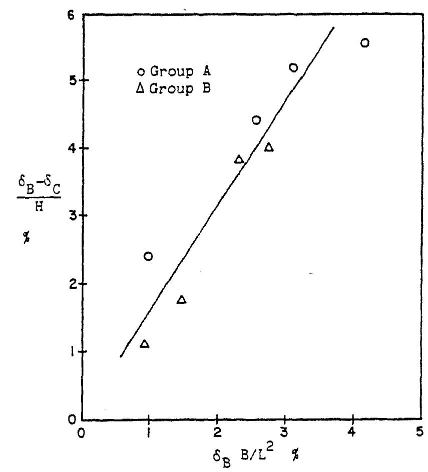


FIGURE 6. NON-DIMENSIONAL LIMIT STRAIN PLOT

CONCLUSIONS

This paper describes in detail a preliminary model study to investigate the possible damage and rupture of a homogeneous embankment dam due to fault movement in a small centrifuge. Based upon the measurements and observations of the model study, the following tentative conclusions may be stated.

1. Crest displacement can be related to basement fault movement.

2. It appears that the crest length to dam height, L, must be included in dimensionless parameters used to interpret the scaled model tests as it may affect the type of failure mechanism experienced by a dam.

3. The different failure mechanisms of dams can produce quite different crack patterns which, in turn, will have potentially different effects on water leakage, erosion and possible collapse of the dam.

It should be emphasized that results obtained from this study should not be quantified for engineering use as yet. However, the feasibility of using centrifuge model to study the problem is well established. Most significantly, the study demonstrates the need for larger models to be tested in a large centrifuge.

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