SENSITIVITY STUDIES FOR DYNAMIC ANALYSES OF GRAVITY ARCH DAMS

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SUMMARY

Sensitivity studies have been conducted on three-dimensional analytical models of two alternative schemes for the modification of Theodore Roosevelt Dam. These studies investigate the effects of modal participation, existing dam modulus, and foundation modulus on dynamic stresses. Models were developed for the SAPIV computer program using eight-noded, type 5 elements to represent both dam and foundation. Response spectrum analyses were performed with a constant spectral acceleration of 0.56 g. A comparison of cantilever stresses is made at upstream and downstream face locations. Results of these sensitivity studies gave a fundamental understanding of the structural behavior of the two models.

INTRODUCTION

Recent hydrologic studies at Roosevelt Dam have indicated a need to raise the structure a minimum of 40 feet. Furthermore, a seismic review has established an MCE (maximum credible earthquake) at the site of M 5.5 at 5 km. Two proposed schemes to accomplish this modification were analyzed for the MCE loading. To aid in the analysis of each scheme, several sensitivity studies were conducted. The first of these studied the effect of modal participation on dynamic stress to determine the number of modes required to produce complete results. A composite modulus of elasticity for the existing material was difficult to determine since Roosevelt Dam is constructed of rock blocks bonded together with mortar. For this reason, a second study was completed to determine the sensitivity of the existing dam modulus to dynamic stresses. Finally, a similar study was made of the foundation modulus. This study also investigated the adequacy of using a fixed foundation for each model.

ANALYTICAL MODELS

The existing Roosevelt Dam is a cyclopean masonry (rock and mortar), gravity-arch structure having a radius of curvature of 420 feet. The dam is 275 feet high with a thickness at crest (elevation 2141) of 16 feet and at the base (elevation 1866) of 150 feet. The upstream face has a batter of 0.05 up to elevation 2081 and then becomes vertical. The downstream face has a slope of 0.67 to 1.0 that becomes tangent to a circular curve of 140-foot radius at elevation 2064.24.

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In the first modification scheme (Model 1), the crest is raised vertically to elevation 2181 with the added section having a constant thickness of 16 feet.

For the second scheme (Model 2), both the height and thickness of the structure are increased. The upstream face is raised vertically to elevation 2181, while the slope of the downstream face is increased to 0.5 to 1.0 above elevation 1947 becoming tangent to a circular curve of 135.55 radius at elevation 2120.30. The crest thickness is again 16 feet.

The finite element meshes developed for each scheme are identical except for the cross-sectional dimensions previously described. Each dam mesh contains 156 type 5 (8-noded brick) elements placed in 3 vertical layers of 52 elements. Each resulting mesh has 6 arches and 12 cantilevers.

The foundation mesh used for both models contains 384 elements arranged in 6 vertical layers. Three layers are located below the dam, two upstream and one downstream. The depth of the foundation is equal to the height of the dam and decreases toward each abutment in a stair-stepped pattern. At the crest, the foundation extends radially about 150 feet. Figures 1a, 1b, and 2 show these models.

LOAD AND PROPERTIES

All sensitivity studies were conducted under dynamic loading conditions. A constant 0.56-g acceleration spectrum is used (rather than the MCE) to eliminate any influence of ground motions. The spectrum is a representative average of the accelerations observed in the MCE spectrum over the range of structural frequencies. Only excitations in the upstream - downstream direction are included. The effects of water mass are not included in any sensitivity study.

The existing dam material (rock and mortar) is assumed to act as a homogeneous isotropic material, as is the concrete in the modified sections. A modulus of elasticity of 5.0×10^6 lb/in^2 is used for both materials except where the sensitivity of the existing dam material is in question. There, the existing material modulus ranges from 5.0×10^6 to 8.0×10^6 lb/in^2 which is consistent with laboratory test results (Ref. 1).

The foundation was modeled as a massless continuum of elements. Foundation modulus values of 2.5×10^6 and 1.5×10^6 lb/in^2 were used for the modal participation and existing dam modulus studies, respectively. In the foundation modulus study, values ranged from 1.0×10^{99} (fixed) to 1.5×10^6 lb/in^2.

A density of 160 lb/ft^3 was used for the existing dam material in Model 1, while a value of 150 lb/ft^3 was used in Model 2. The change here is due to a reassessment of this property between the time that the two models were analyzed. This difference is not considered significant since a direct comparison of stresses between the two models is not intended. Material properties are summarized in table 1.

ANALYSIS PROCEDURE

As previously stated, all studies were conducted using the SAPIV (Structural Analysis Program IV) (Ref. 2) computer program, following identical procedures for both models. In the study of modal participation, cumulative stresses were computed with the inclusion of between 1 and 10 modes. Existing dam modulus values of 8.0 x 10^6, 6.5 x 10^6, and 5.0 x 10^6 lb/in^2 were used to study the sensitivity of that parameter. For Model 1, all elements were designated as existing dam except for the three layers in the top arch. Existing dam elements in Model 2 were the upstream layer below the top arch, the middle layer below the second arch, and the downstream layer below the fourth arch. The foundation modulus study compared stresses for a fixed foundation and modulus values of 2.5 x 10^6 and 1.5 x 10^6 lb/in^2.

RESULTS

Since cantilever action was predominant in both models, only vertical stresses are summarized. For the sake of brevity, results are shown for elements 18 and 19 (upstream face) and 122 and 123 (downstream face), where the more significant stresses occurred. The sensitivity of these elements is representative of the overall sensitivity of each model.

Model 1

Stresses in this model reached their ultimate values with the inclusion of the first eight modes in the analysis. An unexpected observation is that the stress contribution from modes 6 through 8 is three to four times greater than the contribution from modes 3 through 5.

Results of the existing dam modulus study at first appeared inconsistent. As the modulus value was increased, stresses in elements 18 and 122 increased, while stresses in neighboring elements 19 and 123 showed little change. A review of stresses throughout the model revealed a generally symmetric stress distribution for the 5.0 x 10^6 lb/in^2 modulus and an axisymmetric distribution for the 8.0 x 10^6 modulus. An intermediate stress state was noted for the 6.5 x 10^6 lb/in^2 modulus. Upon further examination, the source of this shift in stress distribution was found to be a change in the first two modes among the respective modulus values.

The foundation modulus study shows this model to be sensitive both to the type of foundation (fixed versus flexible) as well as to the degree of flexibility within the foundation. Results for Model 1 are summarized in in table 2.

Model 2

Maximum stresses in Model 2 are attained with the participation of the first five modes.

Results of the existing dam modulus study show that an increase of this parameter transfers stress from the downstream face (elements 122 and 123) to the upstream face (elements 18 and 19). This is expected since elements 18 and 19 are designated as rock and mortar while elements 122 and 123 are within the concrete section (fig. 1a and 1b).

The foundation modulus study shows an increase in stress with a flexible foundation; however, the degree of flexibility has little effect on stresses. Results for Model 2 are shown in table 3.

Although a direct comparison of results for the respective models may not be valid, a contrast in their structural behavior is apparent. Model 1 requires the participation of more modes to reach full stress levels than does Model 2. Changes in the existing dam modulus lead to an inconsistent response in Model 1 while the response of Model 2 remains predictable. Stress variations are greater in Model 1 than in Model 2 for changes in the foundation modulus. For both models, the use of a fixed foundation seems to be inadequate.

CONCLUSIONS

The degree of sensitivity to modal participation, existing dam modulus, and foundation modulus differ greatly in each model.

The studies indicate that in a full dynamic analysis, results for Model 2 would be more reliable than results for Model 1.

Sensitivity studies, as described in this paper, are a useful and necessary tool in the analysis of structures under dynamic loads. They should be considered both in the development of an analysis and in the evaluation of results.

REFERENCES

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[2] Bathe, K. J., E. L. Wilson and F. E. Peterson, "SAPIV - A Structural Analysis Program For Static and Dynamic Response of Linear Structures," Report No. EERC 73-11, College of Engineering, University of California, Berkley, 1973.

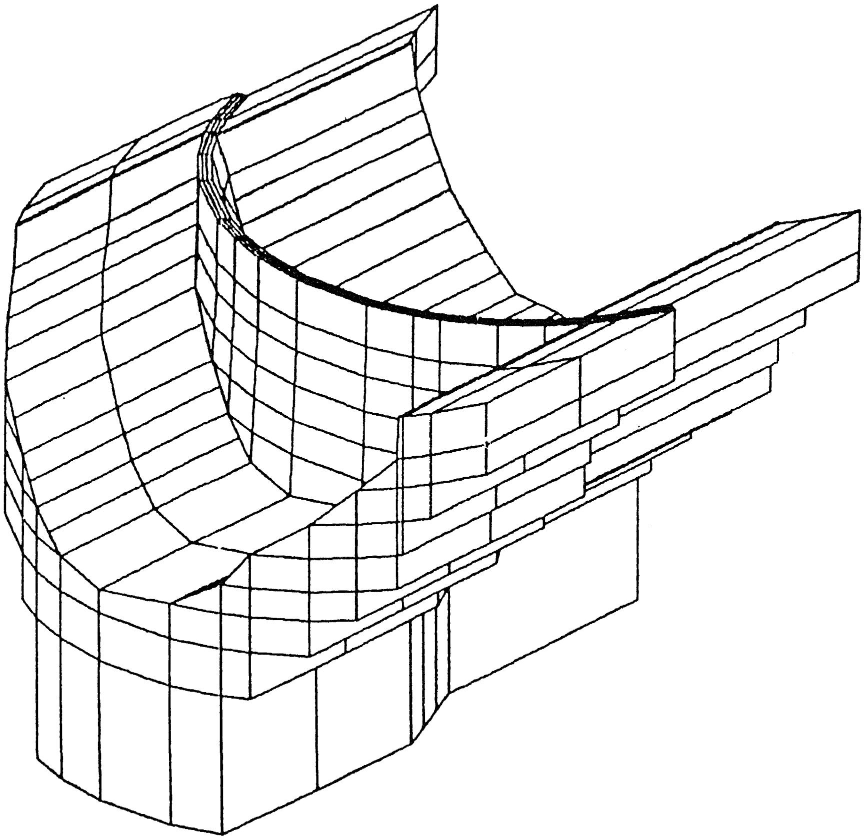
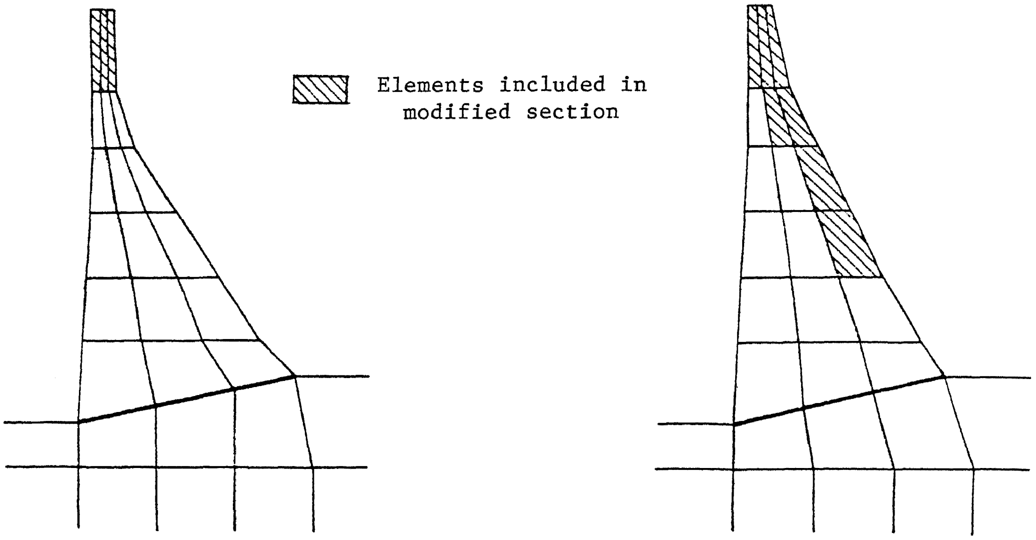


Figure 2. - Orthographic view of Model 2.

Table 1. - Summary of modulus values for studies

Sensitivity study	Dynamic modulus of elasticity (x 10^6 lb/in^2) Existing dam	New concrete	Foundation
Modal participation	5.0	5.0	2.5
Existing dam modulus	Varies	5.0	1.5
Foundation modulus	5.0	5.0	Varies



MODEL 1

MODEL 2

Figure 1a. - Cross sections.

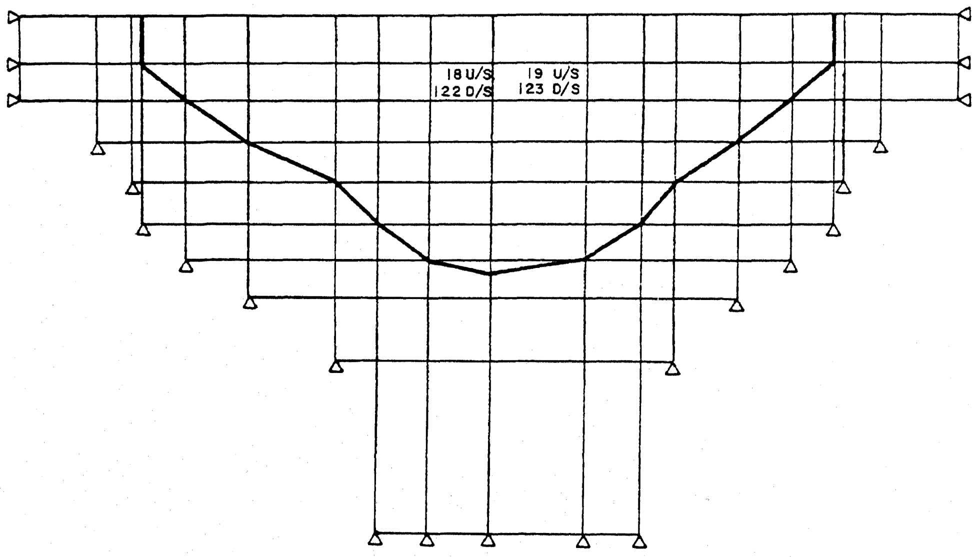


Figure 1b. - Typical mesh developed along dam axis.

Table 2. - Results - vertical stress (lb/in^2)
(In the plane of element faces)

Model 1

Modal participation

Modes	Elements			
	Upstream face		Downstream face	
	18	19	122	123
1-2	295	325	246	268
3-5	315	336	266	282
6-8	373	402	325	347
9-10	373	402	326	347

Existing dam modulus

Modulus	Elements			
	Upstream face		Downstream face	
	18	19	122	123
5.0×10^6	454	470	400	410
6.5×10^6	482	466	423	412
8.0×10^6	615	468	535	420

Foundation modulus

Modulus	Elements			
	Upstream face		Downstream face	
	18	19	122	123
Fixed	321	328	279	285
2.5×10^6	373	402	326	347
1.5×10^6	454	470	400	410

Table 3. - Results - vertical stress (lb/in^2)
(In the plane of element faces)

Model 2

Modal participation

Modes	Elements			
	Upstream face		Downstream face	
	18	19	122	123
1-2	266	240	211	188
3-5	359	331	295	273
6-8	359	331	296	273
9-10	359	331	296	273

Existing dam modulus

Modulus	Elements			
	Upstream face		Downstream face	
	18	19	122	123
5.0×10^6	357	339	293	277
6.5×10^6	392	368	286	267
8.0×10^6	418	391	276	256

Foundation modulus

Modulus	Elements			
	Upstream face		Downstream face	
	18	19	122	123
Fixed	298	276	246	228
2.5×10^6	359	331	296	273
1.5×10^6	357	339	293	277