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SOIL-STRUCTURE INTERACTION EFFECTS ON DYNAMIC RESPONSE OF MORNING GLORY SPILLWAY

LELIO H. MEJIA[1], PAUL W. RIDLEN[2], AND LAUREL HARRINGTON[3]

[1]Senior Associate, Woodward-Clyde Consultants, Oakland, California, USA
[2]Assistant Project Engineer, Woodward-Clyde Consultants, Denver, Colorado, USA
[3]Senior Engineer, Seattle Water Department, Seattle, Washington, USA

ABSTRACT

Morning glory spillways have been used at many earth dam sites where it has been unfeasible to locate the spillway on the abutments. These complex structures often include a concrete tower partially embedded within the body of the dam. An in-depth seismic evaluation of a morning glory tower requires careful analysis of its dynamic response and the interaction with its foundation and surrounding embankment. Procedures for dynamic response analysis of these types of structure have not been well established and few such analyses have been reported. The purposes of this paper are to present a rational approach for analysis of morning glory spillway towers and to describe the effects of soil-structure interaction on the dynamic response of an existing structure.

The proposed approach combines 2-D SSI analyses with 3-D structural analyses. Analysis results for an existing tower indicate that under seismic loading, SSI between the structure and the surrounding embankment increases the bending moments and shears in the structure over those calculated assuming a free-standing tower. Thus, it appears that SSI plays a major role on the behavior of the tower and that neglecting SSI effects may lead to an unconservative assessment of the static and seismic stresses in the structure.

KEYWORDS

Earthquake engineering, soil-structure interaction, spillway towers, morning-glory spillways, drop-inlet spillways, earth dams, structural analysis, finite element analysis, seismic analysis.

INTRODUCTION

Morning glory spillways, also known as glory-hole or drop-inlet spillways, have been used at many earth dam sites where it has not been feasible or economical to locate the spillway on the abutments. Such spillways are complex structures that often include a vertical concrete tower partially embedded within the body of the dam. Because the spillway is a critical element of any dam project, an evaluation of its seismic stability is generally required to assess the seismic safety of the dam.

An in-depth seismic evaluation of a morning glory tower requires careful analysis of its dynamic response and the interaction with its foundation and surrounding embankment. Procedures for dynamic response analysis of these types of structures have not been well established and few such analyses have been reported. The purposes of this paper are to present a rational approach for analysis of morning glory spillway towers and to describe the effects of soil-structure interaction (SSI) on the dynamic response of an existing structure of this type.

The approach proposed consists of two stages and incorporates the following steps: 1) developing a 3-D structural model of the tower; 2) developing a 2-D structural model with static and dynamic characteristics equivalent to the 3-D model; 3) using 2-D and pseudo 3-D finite element analysis methods to analyze the static and dynamic interaction between the tower and the embankment; and 4) using the calculated displacements from the SSI analyses together with the 3-D structural model to calculate stresses in the tower.

The four-step approach allows evaluation of the 3-D stress distribution in the tower due to static and dynamic loads, without performing a computationally-heavy and labor-intensive fully 3-D SSI analyses. It also enables superposition of the response of the tower in two orthogonal horizontal directions.

The proposed approach was used to analyze the dynamic response to strong earthquake shaking of the morning glory spillway tower at Tolt Dam. Tolt Dam is a 60-m-high earthfill dam located about 50 km east of Seattle, Washington, on the north-west coast of the United States. The dam impounds a reservoir with a capacity of about 70 million cubic meters. The spillway tower, constructed in 1962, consists of a 50-m-high cylindrical concrete tower with an outside diameter of 7.9 m and an inside diameter of 5.5 m, founded on a massive concrete thrust block which includes a 90-degree elbow leading to a 5.5-m-diameter discharge tunnel, as illustrated in Fig. 1. The structure is embedded to a depth of 40 m within the upstream shell of the dam.

The results of analyses on the Tolt Dam spillway tower indicate that under seismic loading, interaction between the structure and the surrounding embankment increases the bending moments and shears in the structure with respect to those calculated assuming a free-standing tower. Accordingly, it may be concluded that SSI plays a major role on the static and dynamic behavior of the tower and that neglecting SSI effects may lead to an unconservative assessment of the static and seismic stresses in the structure. This paper presents the results of the 2-D SSI analyses of the structure performed for step 3 of the approach described above.

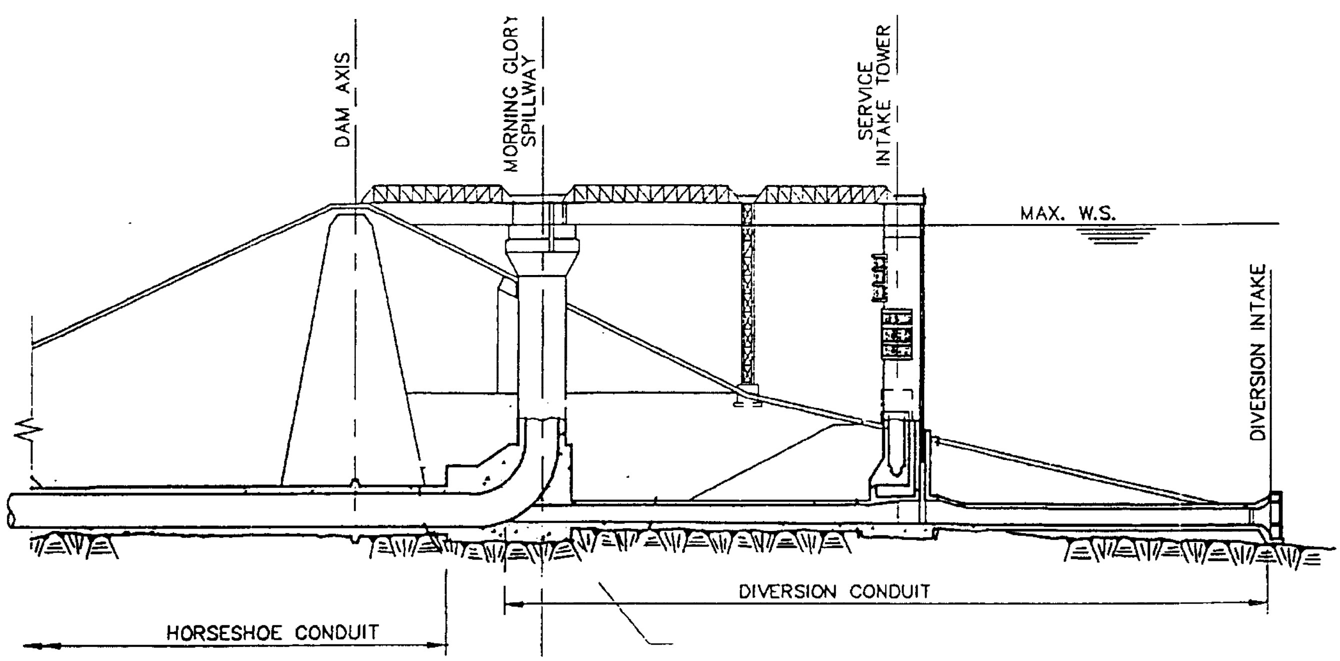

Fig. 1. Schematic Cross Section of Tolt Dam and Morning Glory Spillway

ANALYSIS APPROACH

The approach was used to evaluate the seismic stability of the Tolt Dam spillway tower. It enabled the interaction effects between the tower and the surrounding embankment and reservoir to be assessed. The 2-D static SSI analyses were performed using the computer program SSCOMP (Boulanger, *et. al*, 1981). Steady-state seepage forces within the embankment were computed using the computer program SEEP (Wong and Duncan, 1984). The programs FLUSH (Lysmer, *et. al.*, 1975) and SuperFLUSH (EETC, 1983) were used for the dynamic analyses. The results from these analyses were used to calculate the stresses induced in the tower with a linear-elastic 3-D finite element model and the computer program IMAGES-3D (Celestial Software, 1990).

The 2-D structural models were configured to capture the structural characteristics of the 3-D model. The static 2-D model had equivalent mass and stiffness characteristics as the 3-D model. The dynamic 2-D model also had the same mass distribution as the 3-D model; however, the stiffness was calibrated to match the frequency response of the 3-D model. The first mode of vibration in the plane of each of the 2-D models was given the most weight in the calibration.

ANALYSIS MODEL

Finite Element Model

The finite element model of the transverse section of the dam is illustrated in Fig. 2. The longitudinal model is presented in WCC (1993). The outline of the spillway tower and thrust block are shown with a heavy line. This model was used for both the SSCOMP and FLUSH analyses. For the SuperFLUSH analyses, two additional rows of elements were added to the bottom of the mesh, as discussed later. As illustrated, an intake tower was also modeled; however, the effects of this tower on the embankment response were minimal. The tower structures were modeled using one-dimensional beam elements, while the concrete thrust block was modeled with solid elements assigned the properties of concrete. The concrete was modeled as a linear elastic material with a modulus of 10 MPa and Poisson's ratio of 0.2. The elements inside the spillway tower were modeled using both void elements and solid soil elements. Sensitivity analyses revealed negligible differences between the results using void elements and the results using solid elements inside the tower.

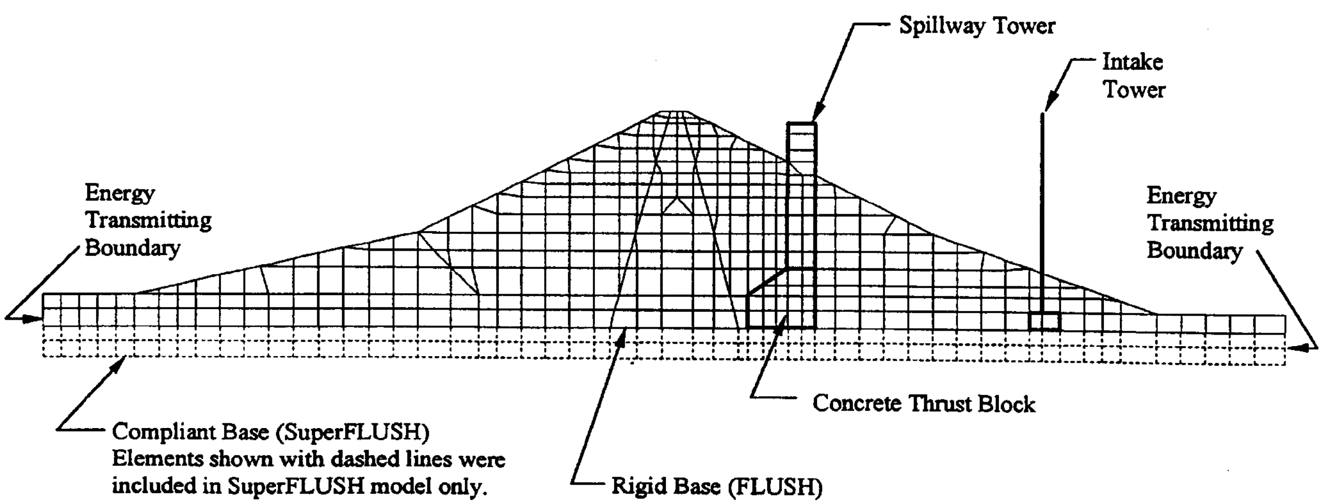

Fig. 2 Soil-structure interaction finite element model (transverse section).

Material Properties

Embankment material properties were derived from exploratory borings, shear-wave velocity measurements, and laboratory tests on samples from borings and test pits. Tests included index property tests and direct simple shear; cyclic direct simple shear; isotropically consolidated-undrained triaxial; and cyclic triaxial strength tests.

Static Properties. The nonlinear behavior of the embankment and foundation soils under static loading was modeled using the hyperbolic soil model developed by Duncan *et al.* (1980). Table 1 presents the parameters used in the SSI analyses. These parameters correspond to drained loading conditions to simulate the long term behavior of the embankment.

Dynamic Properties. The embankment parameters used in the dynamic SSI analyses are also summarized in Table 1. The small-strain shear modulus, A_{max} of the embankment and foundation soils was assumed to depend on the effective confining pressure in accordance with the equation proposed by Seed and Idriss (1970).

$$G_{max} = 1000\ K_{2max} \sqrt{\sigma'_m} \qquad (1)$$

where s'_m is the mean effective confining pressure in pounds per square foot (psf; 1 psf = 48 Pa), and K_{2max} is a factor which depends on shear strain, relative density, maximum particle size, gradation, and other parameters. To model the degradation of shear modulus with shear strain, the modulus reduction relationship recommended by Seed and Idriss (1970) for sands was used. The variation of damping ratio with shear strain was represented using the relationship for sands recommended by Seed and Idriss (1970).

Table 1. Embankment material properties.

Material	Total Unit Weight (kg/cu m)	Static Properties[1]										Dynamic Properties	
		f_o	Df	C (kPa)	K (MPa)	n	R_f	K_b (MPa)	m	K_{ur} (MPa)	K_o	K_{2max}	Poisson's Ratio, n
Core	2320	40	5	0	4.13	0.4	0.7	3.10	0.2	6.20	0.6	150	0.35[3]/0.45[4]
Shell	2240	42	5	0	3.45	0.7	0.8	5.51	0	5.17	0.6	150	0.35[3]/0.45[4]
Random Fill	2320	40	5	0	4.13	0.4	0.7	3.10	0.2	6.20	0.6	150	0.35[3]/0.45[4]
Select Clay	1950	25	0	14.35	0.69	0.5	0.7	0.69	0	1.03	0.5	50	0.49[4]
Rock	2560	Rock not modeled in static analyses.										Note 5	0.40[4]

Notes: 1) See Duncan, *et al.*, (1980) for description of hyperbolic parameters; 2) Damping of 2% assumed for rock; 3) Unsaturated; 4) Saturated; and 5) Rock modulus based on shear wave velocity of 1070 m/s.

LOADING CONDITIONS

Loading conditions included all static loads under normal operations plus the residual load induced during construction of the embankment. Extreme loading conditions included the static loads plus dynamic loads induced by the MCE. The various loads considered in the analyses are described below.

Static Loads

Static loads on the spillway tower consist of gravity loads, hydrostatic pressure, temperature effects, and embankment earth pressure. Stresses due to temperature differentials between the inside and outside of the tower were calculated using a distribution of temperatures based on measurements made at another morning glory spillway at a nearby dam.

The embankment earth pressures were calculated using the finite element computer program SSCOMP. The other aspects of the behavior of soils under static loading such as stress-strain nonlinearity, stress dependency of bulk and elastic moduli, and unloading-reloading behavior.

Dynamic Loads

Dynamic loads on the spillway tower were associated with earthquake ground motions. Two sets of ground motions were used, corresponding to random crustal earthquakes of M_w 6.5 at a distance of 10 km and M_w 7.0 at 16 km (WCC, 1992). Both ground motions consisted of two orthogonal horizontal motions and a vertical motion. The peak horizontal ground accelerations were 0.5g for the M_w 6.5 MCE and 0.40g for the M_w 7.0 MCE.

Hydrodynamic pressure, produced by the interaction between the reservoir and the structure during earthquake shaking, was simulated with added masses calculated using the Goyal and Chopra (1989) procedure. Dynamic earth pressure on the tower due to the dam embankment was calculated in the dynamic SSI analyses described later.

STATIC SSI ANALYSIS RESULTS

Figure 3 illustrates the distribution of stresses, in the form of contours of major principal stress, computed in the static SSI (SSCOMP) analyses. Figure 3a presents the contours for a section without the tower and Fig. 3b shows the results with the tower present. A comparison between the two cases shows that the tower has a significant effect on the distribution of stresses. The analyses show that the tower is very rigid and carries a significant amount of the embankment loading. The stresses upstream from the spillway decrease considerably just upstream of the base of the spillway. Figure 3b also illustrates that the stresses in the upper reaches of the tower, below the surface of the embankment, are diminished. This is the result of a zone of select clay backfill placed on the downstream face of the tower.

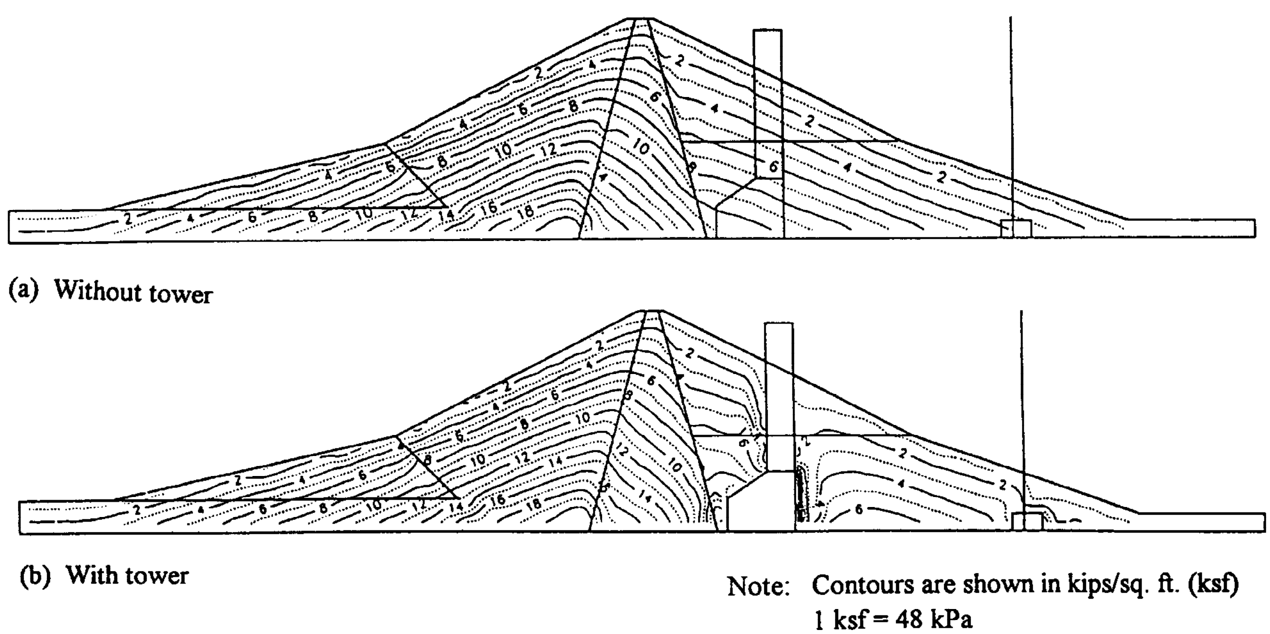

Fig. 3. Results of static SSI analyses shown as contours of major principal stress.

DYNAMIC SSI ANALYSIS RESULTS

FLUSH Analyses

Free-Standing Tower. The spillway tower was first modeled as a free-standing structure, i.e. without the surrounding soil. This analysis was completed partly to verify the agreement between FLUSH and IMAGES3D, but more importantly to evaluate the effects of the embankment on the tower. Both transverse longitudinal sections of the tower were modeled. The tower was also modeled with and without hydrodynamic masses. The natural frequency of the tower calculated by the 2-D (FLUSH) model matched the natural frequency calculated by the 3-D (IMAGES3D) model.

The analysis of the free standing tower indicated that (1) the longitudinal and transverse models yielded approximately the same results; and (2) the addition of hydrodynamic masses had a relatively small effect on the induced accelerations or the natural frequency of the tower, but the moments and shears at the base of the tower were increased by about 25 to 30 percent.

Soil-Structure Model. The effects of soil-structure interaction were analyzed for both the longitudinal and transverse sections. Stresses computed in the static SSI analyses were used to estimate the shear moduli, G_{max}. FLUSH allows a pseudo-3-D analysis by applying a viscous boundary in the out-of-plane dimension. Therefore, both 2-D and pseudo-3-D analyses were completed on the longitudinal section. Pseudo-3-D analyses were not possible on the transverse section because of the geometry of the dam cross section. The analyses on the longitudinal section indicated that the 2-D case underestimated the loads applied to the structure during earthquake shaking, compared to the pseudo 3-D case.

SuperFLUSH Analyses

SuperFLUSH allows the use of a compliant (i.e., non-rigid) base. This models the actual in-situ conditions better because the bedrock is not entirely rigid and exhibits some flexibility. To avoid modeling difficulties encountered when connecting a massive, very rigid structure (i.e., the spillway tower and thrust block) surrounded by relatively soft soil directly on a compliant base, the model was modified by putting two rows of solid elements representing bedrock between the bottom of the thrust block and the compliant base.

As expected, the SuperFLUSH analyses resulted in lower moments and shears in the tower than those calculated by the analogous analyses completed using FLUSH. Figure 4 compares the computed results of the freestanding tower analyses with the 2-D FLUSH analysis results and the pseudo 3-D SuperFLUSH analysis results for the transverse section. Figure 5 compares the same cases for the longitudinal section.

CONCLUSIONS

Provided the calibration of the 2-D models and the transfer of the soil-structure interaction results are properly done, the two-stage approach has the following advantages:

- It is more cost-efficient and flexible than a full 3-D soil-structure interaction approach.
- It allows the analyst to take advantage of the relatively large variety of available 2-D soil-structure interaction programs to suit specific interests (e.g. the use of SSCOMP in this study to model construction sequence).
- It provides 3-D stress distribution information not available from 2-D soil-structure interaction analyses.
- Loads other than embankment earth pressures can be applied as required for convenience and/or accuracy, and their effects combined.

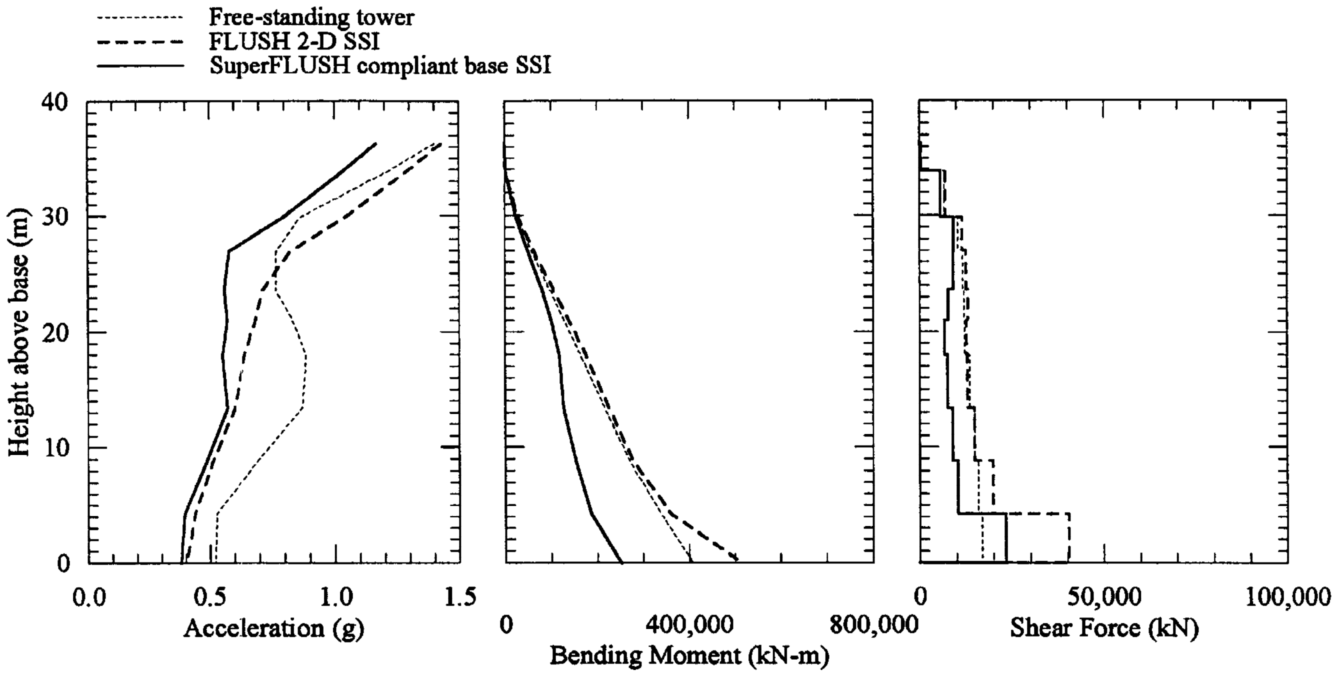

Fig. 4 Results of dynamic SSI analyses on transverse section of Tolt Dam, shown as distribution of acceleration, bending moment and shear force along height of tower.

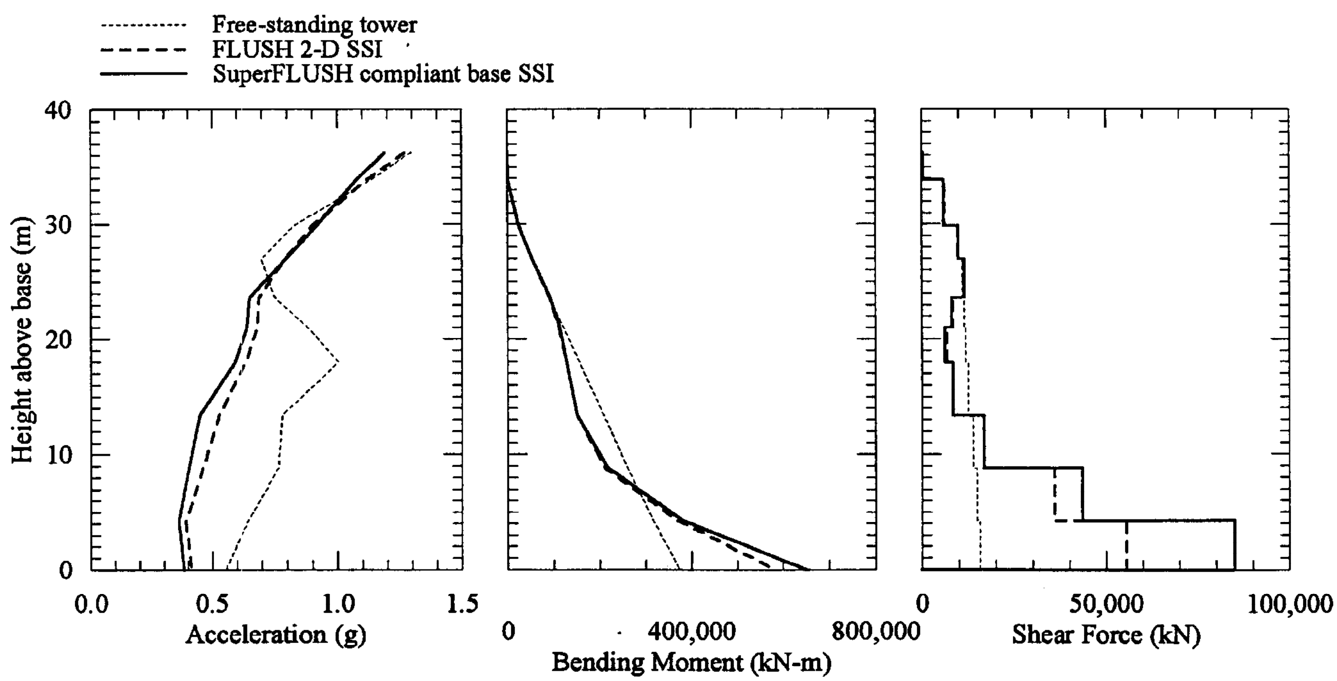

Fig. 5 Results of dynamic SSI analyses on longitudinal section of Tolt Dam, shown as distribution of acceleration, bending moment and shear force along height of tower.

The following conclusions were indicated by the static and dynamic SSI analyses on the Tolt Dam morning glory spillway tower.

- The peak bending moments and shears near the base of the tower are higher for the tower embedded within the embankment than for the free-standing tower.
- A significant difference was observed between the results of the longitudinal and transverse sections in the lower third of the tower, with the peak bending moments and shears in the longitudinal section being significantly higher.
- The pseudo 3-D SSI analyses in the longitudinal direction resulted in higher moments and shears than the 2-D SSI analyses.
- The effects of the compliant base are to reduce the moments and shears calculated in the spillway structure.

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