Assessing a Dam's Structural Properties Using Forced Vibration Testing

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Summary

In the context of the safety assessment of a dam the question after the nature of the boundary conditions in the contact lines dam/surroundings arose. Performance of a Forced Vibration Test with subsequent Finite Element model updating was chosen to answer this question. The dam investigated is a cylindrically shaped reinforced concrete structure with a crest length of 170 m and a height of 46 m. The dam was excited using a 32 kN servohydraulic shaker and its response was measured in 270 points in three directions. Twelve natural modes with frequencies f = 3.6...12.9 Hz could then be identified. Based on the results of these tests an FE model consisting of roughly 3'000 solid, plate and beam elements was updated. The boundary conditions could subsequently be identified as completely clamped-in for the vertical dam/rock interface on the north abutment and as pinned for the south abutment interface and the horizontal interface along the dam bottom line.

Keywords: Assessment; safety; existing structures; dam; forced vibration testing; modal parameters; models; model updating.

1. Introduction

Commissioned by and in co-operation with Vattenfall Utveckling AB, Älvkarleby, Sweden, EMPA performed an experimental and analytical system identification on a dam in Sweden. Due to the rather high costs of these tests they were also subject of an EMPA Research Project. The dam will be referred to as "Norsjö Dam" here. The experimental part included a small preliminary Ambient Vibration Test (AVT) as well as a subsequently performed enhanced Forced Vibration Test (FVT). This procedure is quite common. On the one hand, AVT is cheap and easy and its results allow optimization of the equipment and methodology to be used for the much more expensive FVT. On the other hand, the results of a properly planned and executed FVT are much more informative than those of an AVT. The analytical part included creation of an FE model of the dam including the adjacent structures. As a last step in the procedure, this model was updated based on the FVT results. This combined experimental/analytical investigation allowed determination of a reliable structural model and hence of the structural safety of the dam.

2. The Dam

Norsjö Dam is a cylindrically shaped reinforced concrete structure with a length at the crest of 169.4 m and a maximum height of roughly 46 m (Fig. 1 and Fig. 2). The radius of curvature of the dam upstream face is R = 110 m. The dam width is 2.5 m at the crest and 5.5 m at the bottom of the structure. Construction of the dam was performed by pouring the concrete in vertical strips of 10.6 m width and leaving open intermediate 1.4 m wide gaps. These gaps were filled lateron. It was not clear in the pre-test phase if the dam would behave as a monolithic structure or as a row of independent blocks. This had to be evaluated in a preliminary test on-site.

On the dam downstream side a reinforced concrete wall of 150 mm width is located at a 0.8 m distance of the main structure. This wall and the dam are connected through a large number of reinforced concrete bars of 150 x 150 mm cross section positioned in a grid with a mesh width of 2.9 m. Wooden planks are placed on every second row of these concrete bars which makes the open space between the dam and concrete wall and hence the whole dam downstream face easily accessible. At the dam crest, the dam main structure and the secondary concrete wall are connected through a 4 m wide horizontal reinforced concrete slab of roughly 300 mm thickness.

The dam is founded in rock along its north side vertical boundary and along its bottomline. The south side vertical dam boundary is connected to the first of three large triangular shaped reinforced concrete spillway piers with the two spillways in-between the piers. Adjacent to this spillway construction are two inlet/powerhouse structures. The south side system boundary is an earthfill dam.

Norsjö Dam is part of a system of several dams and reservoirs located on a river over its whole length. The power production regime is typical for a river exploitation system where the powerhouses are located close to the dams' foundations and the difference in height between reservoir level and turbines is comparatively small. The reservoir level is quite stationary at all times. These facts were to be kept in mind when performing system identification tests on the dam.

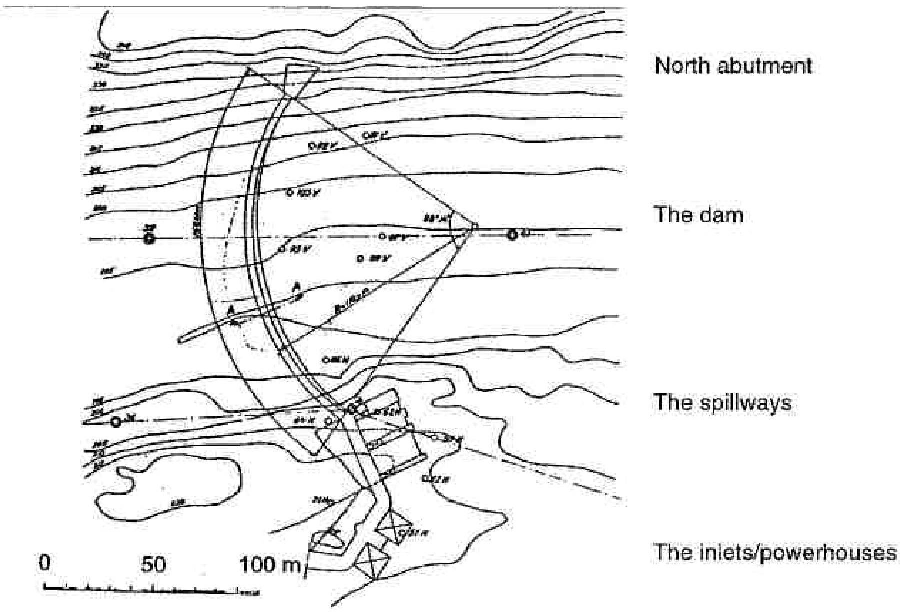

Fig. 1 Plan view of the dam and adjacent structures

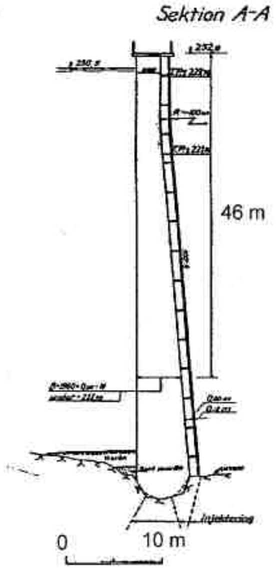

Fig. 2 Dam cross section

3. Preliminary ambient vibration tests

The goal of these tests was to get an idea of the dam fundamental natural frequency. This was of some concern because EMPA disposes of two excitation systems with different capabilities in low-frequency excitation. The structural vibrations excited by ambient sources as wind, waves and microseismicity were measured using three high-performance accelerometers and analysed in the frequency domain. Data processing was performed on-site using an analog-to-digital converter, a laptop computer and specific software. The net testing time was several hours. The main results of the preliminary tests were:

- The dam fundamental natural frequency could be expected to be $f \approx 3.2$ Hz,
- Operation of the two turbine/generator units resulted in significant peaks in the frequency spectra measured.

Considering the low frequency of the dam fundamental mode it was decided to use the more powerful of the two EMPA vibration generating devices for the main tests.

Considering the disturbing effects of the turbine/generator units when operating it was decided to perform the main tests during the times when these were shut down. This meant that measurements could be performed during weekends and nights only.

4. Main forced vibration tests

4.1 The excitation

A servohydraulic vibration generator was used to excite the dam in the horizontal upstream-downstream direction. The main element was a servohydraulic cylinder with a maximum force amplitude F = ±32 kN. The cylinder stroke is 250 mm and it is equipped with a 63 l/min two-stage servo-valve. Steel plates were mounted on top of the piston rod, resulting in a horizontally moving mass of 1'000 kg (Fig. 3). The cylinder is fixed to a supporting steel frame. A load cell is located between the cylinder footing plate and the supporting frame. A rigid connection between the supporting frame and the structure to be excited is provided by ten M20 screws. Fixing of the shaker to the dam crest structural concrete proved to be quite difficult but could be completed in one day.

An air-cooled hydraulic power pack supplied 80 l/min of oil with a 280 bar pressure. The length of the flexible pipes transporting the pressurized oil from the power pack to the shaker being not longer than 20 m, the power pack could not be placed outside the dam. To avoid disturbing influences of power pack vibrations this was placed on air-springs. The power consumption of the whole shaker system is about 90 kW. For field tests in Switzerland, EMPA uses a mobile Diesel aggregate to drive the system. However, for the tests on Norsjö Dam, power was provided by the local power station.

The cylinder was driven displacement-controlled with an electronic control system. The cylinder maximum force amplitude, F = ±32 kN, is reached for frequencies above f = 2.0 Hz. The control signal used for the tests on Norsjö Dam was of a specially designed band-limited random-type. The force spectrum was tuned to be flat in the desired frequency range f = 3.0...16.0 Hz (Fig. 4). Tuning was performed during the pre-test preparation of the equipment at the EMPA laboratories.

Fig. 3 The servohydraulic shaker

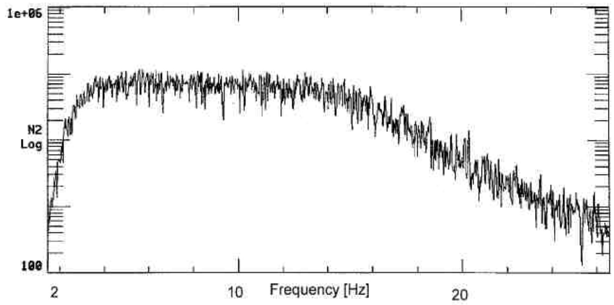

Fig. 4 Power spectrum of the excitation force

Another problem to be solved during the pre-test phase was the choice of the optimum driving point. This choice was based on mode shape calculations performed before the test [1]. This model was based on the known dam geometry and on the assumption that the connection between dam and adjacent rock and structures would be somewhere between pinned and completely clamped-in. Point # 6 of the measurement point grid (Fig. 6) was chosen as a probably good driving point. After having concluded the tests for all measurement points on the dam crest during the first day of testing a preliminary data processing and analysis were performed. The results of these tests were then compared with the FE analysis results. As a consequence, the driving point was rated as being optimal. This was very fortunate because moving of the shaker to a different location would have meant another day of work. (Finally, tests were performed during two days and four nights.)

4.2 Response measurements

The dam vibrations induced by the shaker were measured as accelerations. Three accelerometers with a sensitivity of 10 V/g and a resolution of 10^{-6} m/s^2 were mounted orthogonally to each other on a supporting steel plate being rigidly fixed to the dam structure with the help of screws (Fig. 5).

First, the general structural behavior of the dam had to be evaluated. Two of the abovementioned acclerometer units were hence placed on the two sides of a joint between two blocks. This yielded that no relative movement between the blocks was to be observed. This was no surprise considering the fact that the dam is monolithically reinforced all over the structure. However, in Switzerland, relative movements in joints of a non-reinforced concrete gravity dam of similar size have been observed [2].

The dam response was measured at 227 points distributed over its crest and downstream face in three directions first. The grid point positions on the dam body were uniformly distributed by selecting two measurement points per (12 m wide) block at 4 m distances from the block centerline on the dam crest and repeating this pattern for all the galleries. After completion of this measurement point grid, the grid was extended to the rock foundations and to the spillway and inlet/powerhouse structures where accessible. The number of response measurement points thus increased to 270 (Fig. 6).

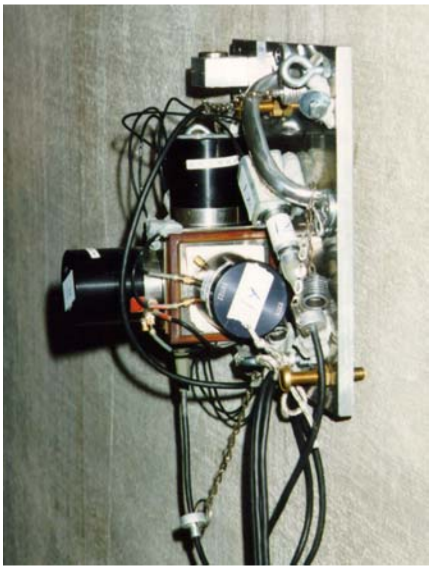

Fig. 5 Three-dimensional acceleration measurement point

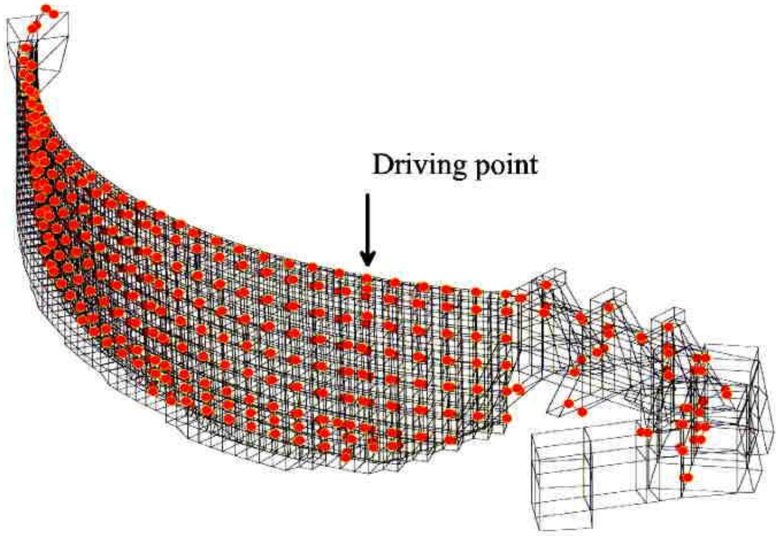

Fig. 6 The measurement point grid (red dots) overlaid with the FE model

4.3 Signal acquisition and processing

An amplifier provided the signal necessary to drive the accelerometers and amplified the incoming signals. Subsequent signal conditioning (anti-alias filtering, after-filtering amplification), 16-bit-digitization and signal acquisition was performed with the help of a dedicated front-end controlled by a computer and using a dedicated software package. Signal acquisition was performed using a sampling rate s = 100 Hz, a time window length T = 41 s and a frequency resolution $\Delta f = 0.024$ Hz. The signals from four three-dimensional measurement points plus the driving point force signal were acquired simultaneously, Fourier transformed and recalculated to obtain a leakage-free estimate of the frequency response functions.

4.4 Results of modal parameter estimation

Modal parameters of Norsjö Dam were estimated using a dedicated software package. Damped natural frequencies, damping ratios and modal participation factors were calculated using the Least Square Complex Exponential Algorithm for the single input case. Twelve natural modes significantly contributing to the dynamic dam response in the selected frequency range f = 3.0...13.5 Hz could be identified. The values of the natural frequencies and damping coefficients given in percent of critical as well the mode shape as valid for the dam crest are presented in Fig. 7. The abbreviations used in this Figure are: A/S = antimetric/symmetric, HB/VB = horizontal/vertical bending. "HB" means that there is no phase change in the shape over the dam height, with "VB" the phase changes once between 0 and π over the dam height The difference in the clamping conditions at the north and south abutments becomes already clear from the crest shape. It is not possible here to graphically display all shapes in three-dimensional form. As an example, Fig. 8 shows this shape for mode No. 9. Discussion of the boundary conditions at the dam bottom line requires animated display of the mode shapes.

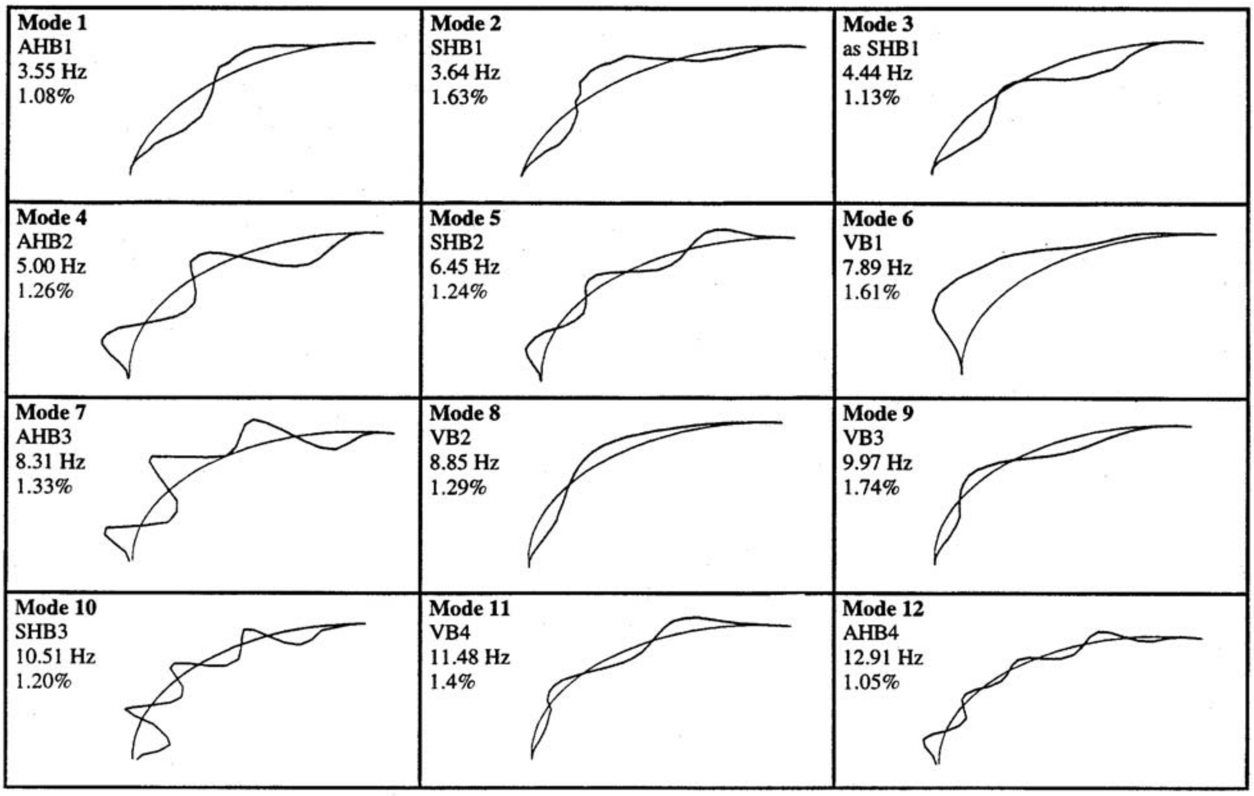

Fig. 7 Mode shapes at the crest as determined experimentally (north abutment to the right). Shape type, frequency and damping in percent of critical are indicated.

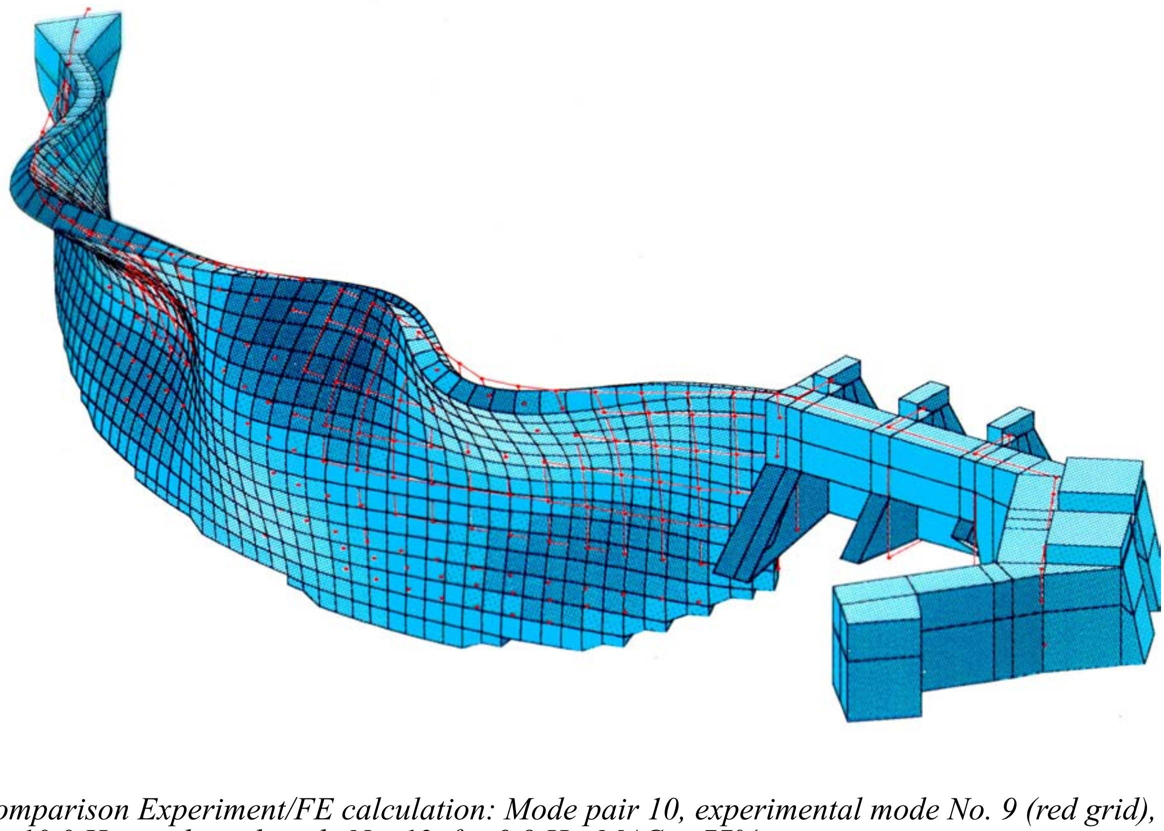

Fig. 8 Comparison Experiment/FE calculation: Mode pair 10, experimental mode No. 9 (red grid), $f = 10.0$ Hz, analytical mode No. 12, $f = 9.8$ Hz, MAC = 77%.

5. Finite element modeling and updating

5.1 Preliminary model

The structural system "dam plus adjacent structures" was modeled using the program MARC. The model consisted of 3'192 solid, plate and beam elements. The Young's modulus was selected as $E_C = 2.4 \cdot 10^{10}$ N/m^2 for concrete and $E_S = 2.1 \cdot 10^{11}$ N/m^2 for steel. The boundary conditions in the structure/rock contact areas were modelled using three elastic springs with a stiffness of $k = 10^{11}$ N/m in the x-, y- and z-direction in each of the respective model nodes of concern. This spring stiffness was selected after some trials during the updating process.

5.2 Model updating

For correlation purposes a dedicated software package was applied on the preliminary FE model incorporating the forced vibration test's results. With minor changes in the modulus of elasticity and stiffness of the soil-structure connection springs it was possible to reach a quite good coincidence between measured and calculated results. (Dam/reservoir interaction was not considered). To quantify the correlation between the respective mode shapes the MAC matrix was evaluated (MAC = Modal Assurance Criterion). The MAC values of the 12 modes obtained from the experiments and their counterparts computed by the FE analysis ranges from 59% to 96%, 100% indicating a perfect coincidence between the two shapes (Fig. 9). As an example, Fig. 8 shows the results for mode pair 10 with a MAC-value of 77%.

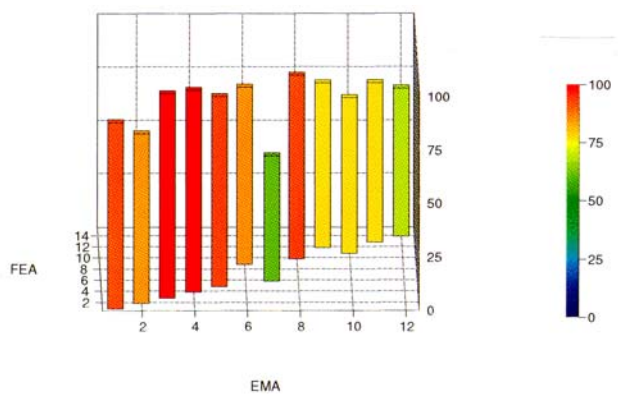

Fig. 9 Graphical representation of the MAC matrix (EMA = experimental, FEA = analytical, mode numbers on both axes).

6. Discussion, Conclusions, Acknowledgements

To reliably determine the structural characteristics of a dam a system identification procedure using the forced vibration testing technology was sucessfully applied. Performance of a preliminary ambient vibration test proved to be useful. This allowed to optimize the methodology and equipment to be used for the forced vibration test. As a result, twelve natural modes of the dam could be identified. A problem with cross-talk between closely-spaced modes with quite different shapes had to be noted. This resulted in a relatively low MAC-value for mode pair 7 involving the first vertical bending mode $f_6 \approx 7.9$ Hz and the third antimetric horizontal bending mode at $f_7 \approx 8.3$ Hz, with MAC = 59% only (Fig. 9). Considering the high MAC-values obtained for the other mode pairs the FE model finally determined can be taken as being as close to reality as possible. Although the results of the procedure described here are valid for small structural displacements only the model was rated to be appropriate enough to be used for further studies of the dam behavior under any kind of load and to hence assess its safety.

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7. References

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