〒New Method of Analysis for Arch Dam:Reservoir and Foundation Dynamic Interactions,and Static Joint Opening(アーチダムの新構造解析法:堤体-水-地盤の相互作用及び静的継手開口について)〒

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論　文　内　容　要　旨

The recent trend to construct concrete arch dams in sites where the conventional qualifications are not satisfied, necessitates further study on more accurate mathematical modellings of these dams to ensure safety. From the structural engineering point of view still there is no convenient and accurate method to do this.

In the field of dynamic seismic response analysis of concrete dams different modellings are proposed by researchers. To include the hydrodynamic effect the general practice is either the added-mass approach or a full inclusion of the fluid domain in the analytical model. The latter does include the interaction whereas the former does not. As a high approximation, the FEM model for interaction analysis has been almost exclusively carried out in the Euler-Lagrangian sense which demands the coupling of a pressure field (reservoir) with a displacement field (dam). This brings about a lot of difficulties such as asymmetric system matrices, large bandwidth, and solution instabilities. On the other hand the full Lagrangian method developed so far is free of such troubles but suffers from certain problems. Current Lagrangian procedures for modelling the fluid-structure interface although do not have severe consequences in the case of flat gravity dams but are considerably inaccurate for a 3-dimensional curved arch dam. Thus such methodes are not matured to be employed accurately. Besides

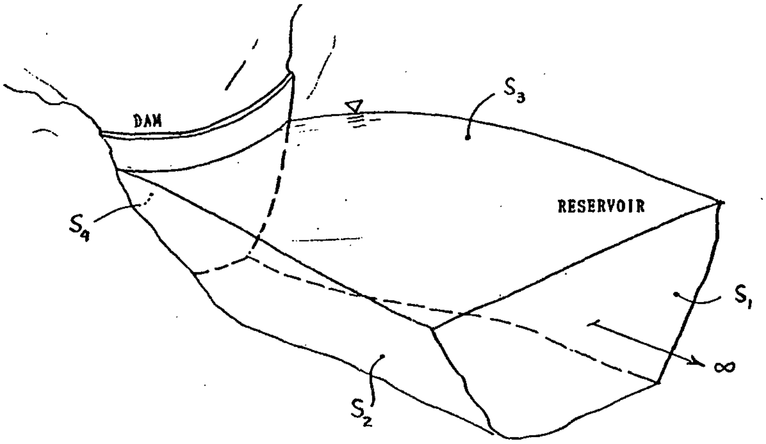
the existence of a large number of zero energy modes, and the cost of analysis may be troublesome.
Furthermore the reservoir of an arch dam is a 3-D body with multi-nature boundaries. As a wide range of frequencies are present in the response, radiation through the reservoir end as well as the reservoir banks wave absorption should never be overlooked.
Finally the foundation interaction has to be included and the inconsistent boundary conditions with prescribed displacements or tractions usually lead to spurious results. Therefore the radiation condition for elastodynamic waves should be employed in three dimensions.
Apart from these the concept of modelling of concrete arch dams which are constructed of jointed monoliths is still far from reality, and methods to account for the foundation joints as well as the construction joints are very desirable. In the static state the opening of such joints is believed to affect the state of stress in the structure as conformed with the actual phenomenon.

In the first part of this research a theoretically consistent as well as practically convenient finite element methodology for the time domain dynamic analysis of arch dam is developed. This methodology is specially very accurate in modelling the solid-fluid interface and for the first time has enabled complete account of the aforementioned dynamic phenomena by the full Lagrangian formulation in an economical manner.

CHAPTER 1 is the introduction in which the motives, the objectives and the conclusions are described in brief.

CHAPTER 2 deals with the modelling of the dam-reservoir system. Arch dam is modelled as an elastic body by high order special parabolic 22-node 3-D shell elements. The acoustic waves in the fluid govern the problem, and a state-of-the-art study on the evolution of reservoir models is assigned mostly in pressure formulation.
The discussion continues to the boundary conditions of the fluid domain. These are introduced below as refering to Fig.1.

1. Radiation on surface S_1
2. Refraction on surface S_2
3. Free surface waves on surface S_3
4. Fluid-structure interaction on surface S_4



F I G . 1 — RESERVOIR BOUNDARIES

The techniques of modelling the radiation boundary are investigated first, and it is found that only the Sommerfeld boundary has the requirements needed. Because it is frequency independent, and could function efficiently in arbitrary geometries when placed not too close to the dam. It is equivalent to a viscouse traction imposed on S_1 expressed as

$$tr_n = \rho C \dot{u}_n \qquad \text{Eq.1}$$

tr_n= normal traction
ρ= unit mass of water
C= velocity of sound in water
$\dot{u}_n$= normal velocity of water particle

This condition contributes to damping.

With the same analogy the wave energy refracted into the bottom flexible material is accounted for by a viscouse traction as

$$tr_n = \rho C \left(\frac{1+\alpha}{1-\alpha}\right) \dot{u}_n \qquad \text{on } S_2 \qquad \text{Eq.2}$$

α=ratio of amplitudes of reflected and incident waves

Furthermore the free surface gravity waves although are not so important, but are deliberately employed in order to arrest the excessive degrees of freedom. This contributes to the stiffness by a boundary traction of

$$tr_y = \rho g\, u_y \qquad \text{on } S_3 \qquad \text{Eq.3}$$

tr_y= vertical traction
g= gravitational acceleration
u_y= verical displacement

Finally the most important is the structure interface which in the Lagrangian sense should satisfy three conditions for the two neibouring domains.

1. Identity of normal displacements.
2. Null tangential forces.
3. Identity of normal forces.

Despite other models, our special 3-D surface interface parabolic isoparametric element could satisfy the first two conditions and although the third condition is not satisfied completely but remarkable accuracy is achieved. This element has been originally developed by Beer for rock mechanics using a relative displacement formulation as

$$f_I = D\Delta \qquad \text{on } S_4 \qquad \text{Eq.4}$$

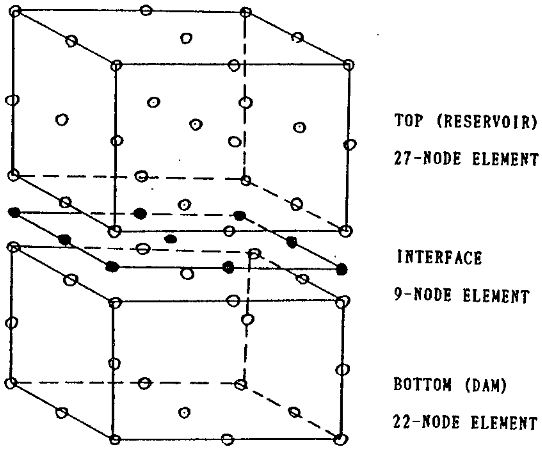
where $f_I^T=[\tau_1,\tau_2,\sigma_n]$

$$D=\begin{bmatrix} C_{s1} & 0 & 0 \\ 0 & C_{s2} & 0 \\ 0 & 0 & C_n \end{bmatrix}$$

$$\Delta^T=[\delta_1,\delta_2,\delta_n]$$

f_I= interface force vector
D= interface elasticity matrix
Δ= interface relative displacement vector
τ_i= interface tangential forces
σ_n= interface normal force
C_{si}= interface tangential stiffness coefficients
C_n= interface normal stiffness coefficient
δ_i= interface tangential relative displacements
δ_n= interface normal relative displacement

We developed a 9-node element with a zero C_{si} and an infinite C_n which insures the special conditions and the compatibility of the fluid and structure.



a) COMPATIBLE PARENT ELEMENTS AT THE DAM-RESERVOIR INTERFACE

FIG. 2 - INTERFACE COMBINATIONS OF ELEMENTS

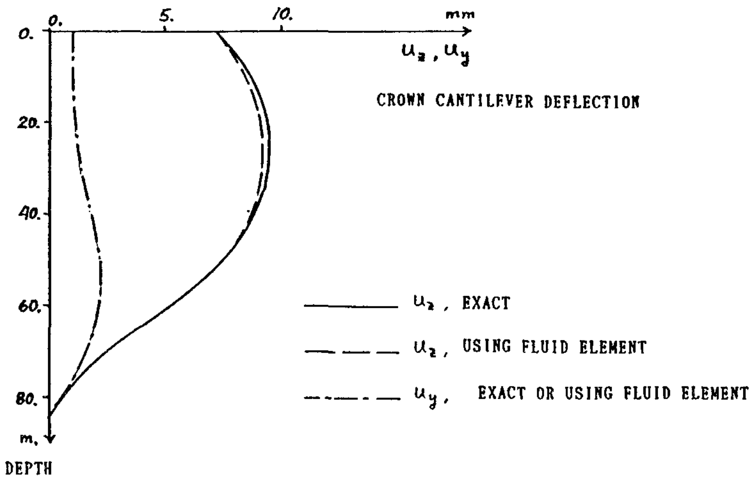
The fluid itself is assummed as inviscid, compressible, and irrotational. An element developed by Wilson is extended to 3 dimensions with one main (volumetric) strain, and three constraint strains (corresponding to rotations). The penalti function and a reduced integration order are employed along with an essentially 27-node parabolic 3-D shape function. The mass matrix of the fluid element is a consistent diagonal one. Few hourglass modes remain but with no apparent effect on the response. The sloshing and the volume-change modes are approximated best for the fluid.

The overall system is governed by a standard FEM structural equation of motion which is solved by direct integration.

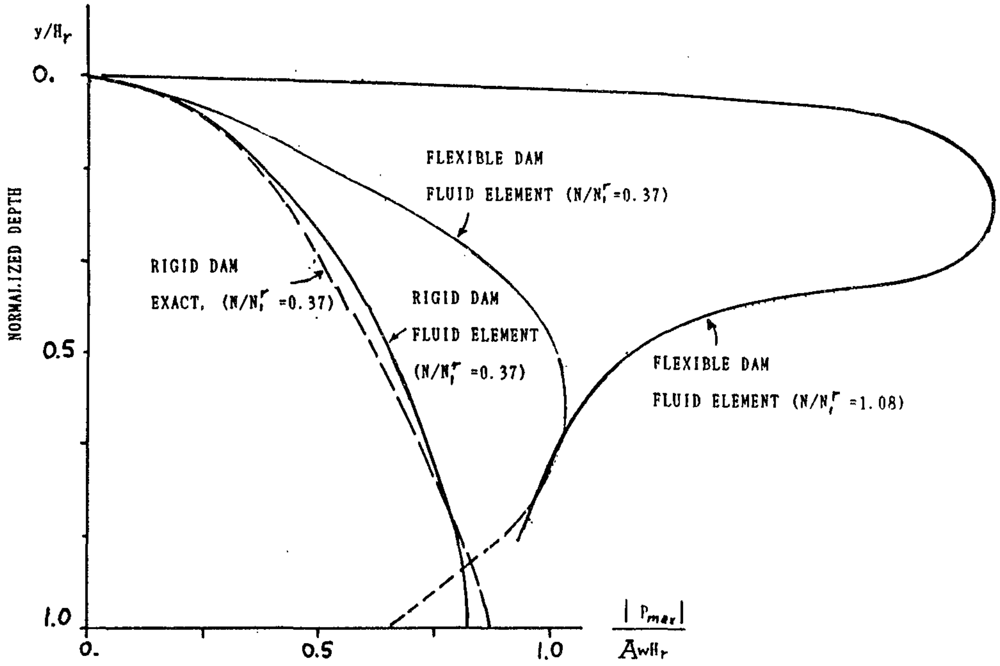
$$\tilde{M}\,\ddot{a} + \tilde{C}\,\mathring{a} + \tilde{K}\,a = F \qquad \text{Eq.5}$$

$\tilde{M}$= mass matrix of the overall system
$\tilde{C}$= damping matrix of the overall system
$\tilde{K}$= stiffness matrix of the overall system
F= external force vector of the overall system
a= nodal displacement vector

Several simple cases have been solved to verify the accuracies of the fluid-structure formulation and its boundaries (see Figures 3,4, and 5).



F I G . 3 – HYDROSTATIC LOADING OF NARUKO ARCH DAM.



F I G . 4 – NORMALIZED MAXIMUM STEADY STATE HYDRODYNAMIC PRESSURE CLOSE TO THE UPSTREAM FACE OF A FLAT DAM

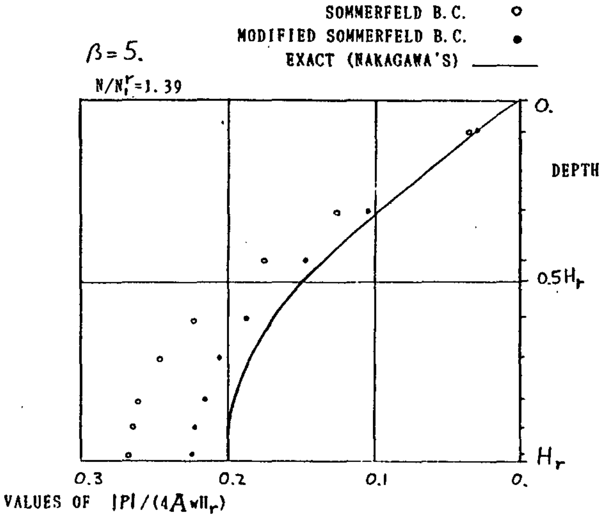


FIG. 5 — STEADY STATE HYDRODYNAMIC PRESSURE PROFILE ACTING ON THE FACE OF A RIGID DAM WHEN THE DAM REACHES TO ITS NEUTRAL POSITION (BOTTOM REFRACTION B.C.)

CHAPTER 3 deals with the foundation. The material (rock) is assumed as linear elastic and the model of foundation is extended with a radii of 0.5-1.0 times the dam height. The standard viscouse boundary is proved to be superior to all other nonreflective boundaries in the three-dimensional arbitrary geometry. This boundary is frequency-independent and able to absorb efficiently all types of waves i.e., P, S, and R waves. It is defined by a viscouse traction whose typical component is written as

$$\sigma = \rho V_K \dot{u} \qquad \text{on } S_5 \quad \text{Eq.6}$$

σ= a traction component (normal or tangential)
V_K= the corresponding wave velocity (K=P, or S)
$\dot{u}$= boundary velocity (normal or tangential)

This kind of boundary condition contributes to the system damping along with the foundation internal damping. The earthquake acceleration is also input to the foundation boundary.

CHAPTER 4 includes the explanations of the dynamic fluid-solid interaction analysis computer program SPRAD along with the other programs.

In CHAPTER 5 two objects are pursued; first, an assessment of the response analysis effectiveness by comparison of the measured and the calculated responses of some realistic Japanese arch dams, second, a comparative study with the most up-to-date Euler-Lagrangian algorithm of fluid-structure analysis. These studies led to the followings (refering to Figures 6,7,8, and 9).

1. Remarkable or fair coincidences between the computational and the measured stream-direction responses were observed.
2. However very little could be expected for such agreements in the case of vertical or cross-stream responses probably as a result of the non-monolithic nature of arch dams as well as uncertainties of the real input motions.
3. As for the comparative study between the Euler-Lagrangian and the present analysis, the two methods remarkably agree in the case of realistic reservoirs.
4. However when the reservoir banks are assumed rigid the results diverge at least in the case of the vertical and the cross-stream motions. The reasons for such disagreements were elaborated.
5. It was also observed that the reservoir banks wave reflection coefficient α has pronounced influence on the seismic response of concrete arch dam. But this effect is not as great as it is claimed by Chopra.
6. The full Lagrangian method for the 3-D seismic analysis of arch dam qualifies most of the capabilities of the competitive Euler-Lagrange approach accurately. Furthermore it is stable, not subjected to numerical difficulties, and straight forward to implement in standard structural FEM codes.
7. Finally our method employs a computationally efficient time domain analysis and thus could be extended for the non-linear dynamic analysis of arch dam in the case of Maximum Credible Earthquake. This capability is not possible in the Euler-Lagrangian method.

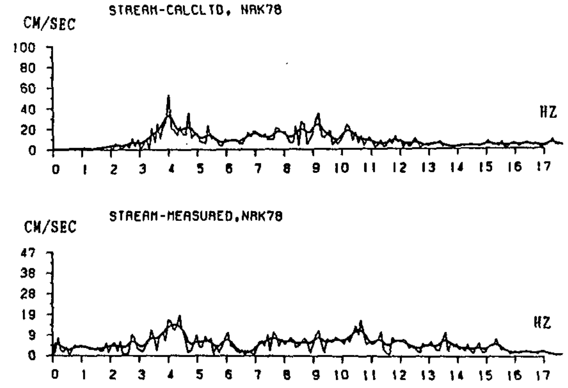
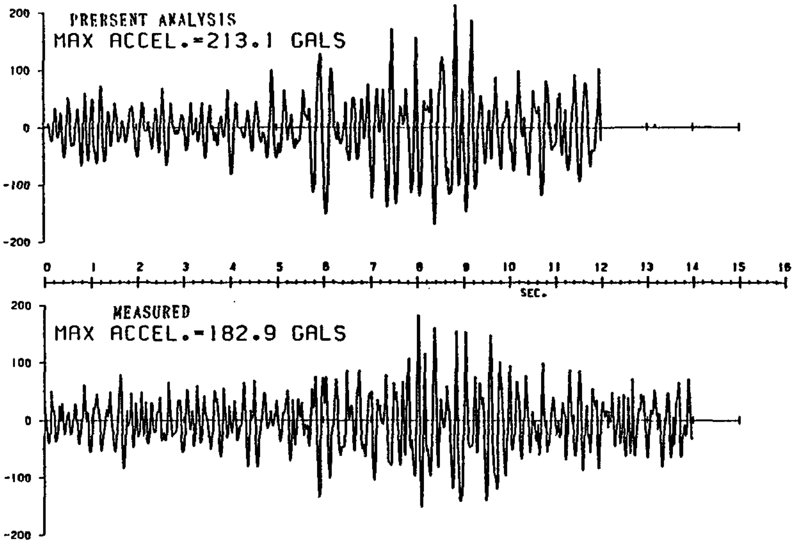
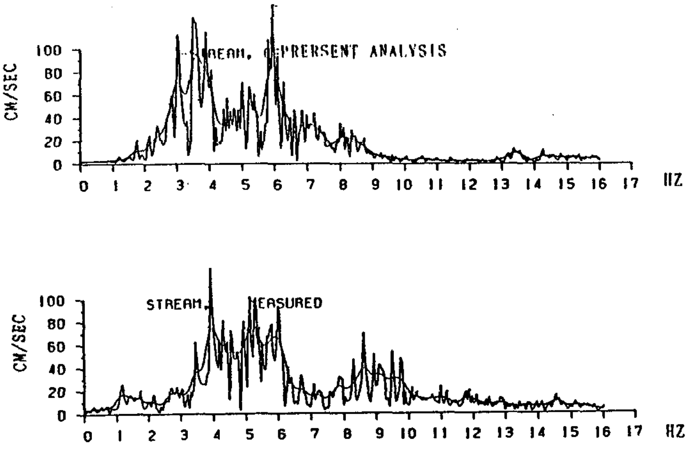


FIG. 6 —COMPARISON OF THE FOURIER AMPLITUDE SPECTRA OF STREAM COMPONENT ACCELERATIONS OF MEASURED AND CALCULATED RESPONSES OF NARUKO ARCH DAM (AT THE GALLERY) DUE TO SIMULTANEOUS 3-D EARTHQUAKE OF 1978. (NOTE THAT THE SCALES ARE DIFFERENT.)



F I G. 7 — COMPARISON OF STREAM COMPONENT ACCELERATIONS OF MEASURED AND CALCULATED RESPONSES OF YUDA ARCH DAM (AT THE CREST CENTER) DUE TO SIMULTANEOUS VETRICAL AND STREAM COMPONENTS OF 1978 EARTHQUAKE.



F I G. 8 — COMPARISON OF THE FOURIER AMPLITUDE SPECTRA OF STREAM COMPONENT ACCELERATIONS OF MEASURED AND CALCULATED RESPONSES OF YUDA ARCH DAM (AT THE CREST CENTER) DUE TO SIMULTANEOUS VETRICAL AND STREAM COMPONENTS OF 1978 EARTHQUAKE.

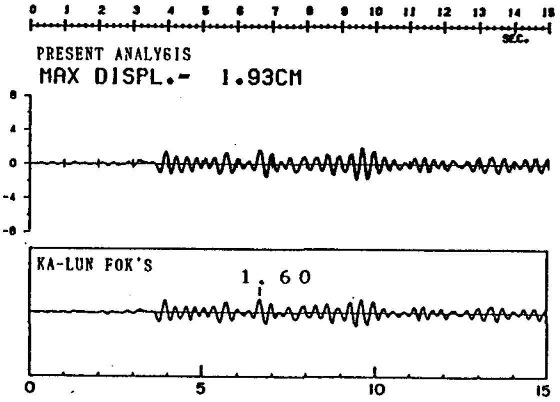


FIG. 9 - CASE 3

DISPLACEMENT RESPONSE AT POINT G ON THE CREST OF MORROW POINT ARCH DAM DUE TO STREAM COMPONENT OF TAFT EARTHQUAKE WITH RESERVOIR FULL. $\alpha = 0.5$

CHAPTER 6 offers a discussion about the joint opening modelling technique and its consequences. The potential joint openings of foundation interface due to the hydrostatic load, and of the construction joints due to the dead load are considered. So far there is no convenient and consistent way of modelling for such phenomena. Thus the author has employed the isoparametric surface element of Chapter 2 for the modelling of the 3-D discrete crack of this problem with a non-linear constitution. The main assumptions are

1. Small displacements.
2. Only crack Mode I .
3. Linear elasticity of concrete.
4. Elasticity of joints except in excessive tension of sample points beyound which they open.
5. Closure of joints upon negative relative displacements of sample points.

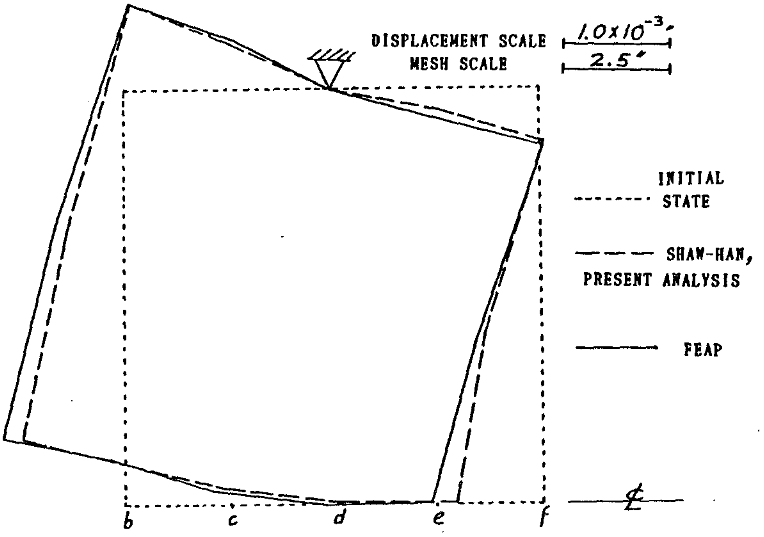
The formulation of the joint element is as discussed in Chapter 2, but this time 8-node elements are employed. C_{s1} or C_n should be decided experimentally. But they get zero when excessive tension occures in the sample point of the joint. The body of dam is composed of 20-node isoparametric elements. Due to the known plasticity theorems when the equilibrium and the yield conditions are satisfied such models could monitor a lower bound state of failure. Direct iteration is used for the non-linear model and thus a desirable safety check has become possible. This joint opening analysis is supposed to enable explaining the gap between the analysis results and those of actual observation or of model tests concerning the tensile stresses in the joints. The accuracy of the model is checked by comparing with other (two-dimensional) methods as those of FEAP or Shaw-Han. By a few hypothetical or realistic examples of arch dams and by refering to Figures 10 and 11, it has been found that;

1. A well designed actual arch dam proved safe against the foundation joint opening when the present method was applied.
2. Contrary to O'Connor, it does not seem that only wide span arch dams are vulnerable to the foundation joint opening. Indeed the stiffer the foundation rock, the higher the risk of foundation joints to crack.
3. The foundation joint opening alters the state of stress in the dam body significantly. And apparently this is in the improving direction.
4. The foundation joint opening increases the arch stresses, but the vertical construction joints opening decreases them in the arch dam body.
5. Significant increase of the radial displacements of arch dam by a factor of 1～2 is expected by either the foundation or vertical construction joint openings.
6. It is clear that neither the full monolithic nor the free monoliths models could warrant the dead load risk and the only reasonable method is the joint analysis one presented here.
7. A study on the relation of the vertical joint opening with the shape of arch dam is felt necessary for future studies in order to assess the influence of overhangs.
8. It seems that both of joint opening mechanisms should be considered simultaneously to enable the actual safety assessment of arch dams.

CHAPTER 7 contains the general conclusions.

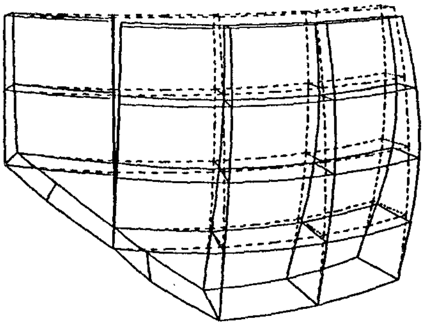
APPENDIX A has the Euler-Lagrangian formulation of the fluid-structure interaction.

APPENDIX B offers the shape functions of the variety of elements developed or used in the study.



a) ONE BLOCK

FIG. 10 — DISPLACEMENT SOLUTIONS OF BLOCK CONTACT PROBLEM.



CASE 1. JOINTED MONOLITHS
(NON-LINEAR)

FIG. 11 — DEFLECTED SHAPE OF THE HYPOTHETICAL HIGH ARCH DAM DUE TO ITS DEAD LOAD. VERTICAL CONSTRUCTION JOINTS.

審査結果の要旨

コンクリートアーチダムは強固な地盤の支持を不可欠とする構造物であって，とくに地震地域においてその安全性を確保するには，水の動的作用の影響だけでなく，基礎地盤の動的支持特性をアーチダムの構造に合理的に反映することが極めて大切である。

本論文は，アーチダムの堤体－水－地盤の全体を1つの系として，有限要素法により，その動的挙動の解析手法を研究し，さらに堤体底面とコンクリート施工継手の静的開口の過程を解析して，アーチダムの耐震性検証の力学的基礎を得ようとしたもので，全編7章よりなる。

第1章は序論で，この研究の必要性を論じている。

第2章は，堤体と水との相互作用について，まず既往の研究の問題点を論じている。また，ラグランジュ座標系を用いて，水の圧縮性を考慮した運動方程式を，堤体曲面に沿う水の自由滑動を許す境界条件の下で定式化し，計算結果を解析的に得られた種々の解と比較して，この方法が精度のよい結果を与えることを示している。この方法は三次元の任位形状を持つアーチダムの解析に一般に適用することが可能であり，有用な成果である。

第3章は，基礎地盤の取扱いについて論じている。とくに，粘性境界を用いて地震波の周波数全域に有効な三次元の境界条件を構成し，非線形問題に拡張している。この手法をアーチダムの堤体－地盤系の解析に適用してその妥当性を示した研究はこの論文が最初である。

第4章は，計算機による演算の手順について述べている。

第5章は，上で構成した解析方法を2つの実際のアーチダムに適用し，計算結果を地震記録と詳細に比較することにより，この方法が流水方向で堤体加速度の観測値によく一致する結果を与えることを示している。

第6章は，コンクリートの変形によって，堤体の底面と一部の鉛直方向の施工継手に，常時の状態で開口部が生ずる恐れがあることを示し，アーチダムの耐震安全性の検証に，その影響の検討の必要が大きいことを論じている。

第7章は結論である。

以上要するに本論文は，コンクリートアーチダムの地震時挙動を三次元の有限要素法を用いて検証する実際的な方法を提示したもので，その成果はコンクリート構造工学の発展に寄与する所が極めて大きい。

よって，本論文は工学博士の学位論文として合格と認める。