# Frequency Content Effects on Nonlinear Behavior of CMD Dam Excited by Earthquake Motion

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## Abstract

In recent years, a new kind of dam called CMD dams (Cemented Material Dam) has been paid more attention Because of its special properties. Although the final volume of CMD dams are further than conventional concrete dams, but it has been consumed less cement per cubic meters because of less required tensile and compression strength. The past studies have proved that the structures have different responses to the earthquakes with the same magnitude. This indicates that maximum earthquake (PGA) earthquake is not the only factor in determining the intensity of earthquakes, and in addition to PGA, the frequency of the earthquake and its duration affect the severity of the earthquake. In this research, the earthquakes with different frequency content and the same duration and PGA have been exerted to defined CMD dam. As a case study, Tobetsu CMD dam configuration in Japan has been utilized for simulating seismic response of this type of dam. The ratio of PGA divided to Peak Ground Velocity (PGV) is an index to categorize frequency content from low to High frequency content.By scaling the PGA of 6 earthquakes to 0.6g and restricting the time duration to 10 second, the seismic impact of frequency content has been investigated. The result shows that the ratio of PGA/PGV as an index of frequency content is not reliable for prediction the damage power of an earthquake on CMD dams. The research also shows that there is a meaningful relationship between the magnitude of the damage power of each earthquake and the proximity of the natural frequency of dam to the corresponding response acceleration of dominant applied earthquake frequency.

**Keywords:CMD Dams,Non-lineardynamical analysis,Frequency content, dominant frequency, damage index.**

## 1. INTRODUCTION

According to human need to dams anddevelopment of this industry, engineers try to reduce the costs and protect the environment. Main idea of CMD dams comes from using more material with lower unit cost instead of minimizes the body material thatneeds to increase their quality. In this dams although the body volume is increased, but by reducing the required resistance, cement consumption will be significantly reduced.At the end of twentieth century, cemented material dams as a new kind of dams with various advantage has been paid more attention. In 1970, Raphael propounds the idea of CMD for the first time in a conference in California. [1]. Then and in the following years, numerous studies have been carried out on the applicability of this dam type and CSG technology. In the most recent studies, Arefian et alinvestigates the seismic evaluation of cemented material Dams -A Case Study of Tobetsu- in 2015. [2]. Aliyari et al investigate theSeismic behavior of CMD dams based on nonlinear constitutive model for dam body material in 2017. [3].Due to construction cost and strategic importance of dams, the potential damage of an earthquake on these dams should be studied. Based on structural seismic response studies, it is determined that thereare 3 important seismic parameters that cause to structural damage: domain, duration and frequency content of an earthquake.When nonlinear response of a multi degree of freedom(MDOF) systems is considered, in thought of many researcher frequency content has the most effect on them.in this research frequency content is considered as one of the main factors of an earthquake that can affect the nonlinear response of structures subjected to earthquake with same magnitude. By using recorded natural earthquake in nonlinear time history analyses, we investigate the frequency content effect on TobetsuDamas a case study of CMD dam.

## 2. NUMERICAL MODELLING

### 2.1. SEISMIC ANALYSIS

In seismic analysis, the response of the structures changes over the time. In these analyzes, time is a real physical quantity and the inertia forces are presented in the dynamic equilibrium equations of structures. Internal forces are caused by the deformation and movement of structures.at seismic loading, the base of structures is subjected by seismic excitations and the response of structure change over the time.In this study, time history analysis method is used for seismic analysis. Time history analysis is the most realistic method available. It calculates the variable response of structures during actual earthquake excitations. For time history analysis, it is necessary to solve the equation of motion over the time. To solve the equation of motion, we have to integrate them in small time intervals and then calculate the structural response over the entire seismic loading period by summation the response in small intervals.

### 2.2. Equations of motion

We consider a monolith of a concrete dam on a rigid bed without water in its reservoir that is exposed to an earthquake that is constant along dam bad. This monolith is a multiple degree of freedom that has two degree of freedom along X and Y for every node point.Equation of motion for this dam monolith modeled by a two-dimensional plane finite element system is:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} - [M]\{1^x\}a^x g(t) - [M]\{1^y\}a^y g(t) \tag{1}$$

Where,[M] and [C] and [k] are mass matrix, viscose damping matrix and stiffness matrix respectively dam finite element structure. u is displacement variable. Structural stiffness and mass matrices are obtained from the corresponding finite element matrices by direct assembly method. {u} is displacement vector relative to free field motion and a g(t) are horizontal component (X) and vertical component (Y) of free field acceleration of earthquake. {F(t)} is external forces vector applied on dam structure. For concrete dam, it can be divided into hydrodynamic forces, {Fp} and consequent of other forces{F1} applied on dam. So the final form of equation of motion becomes in form of equation (2):

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \left\{F_p(t) + F_1(t)\right\} - [M]\{1^x\}a^x g(t) - [M]\{1^y\}a^y g(t) \tag{2}$$

Where, $F_{ix}(t)$ and $F_{iy}(t)$ are the forces acting on the node i in the X and Y direction.
To consider and approximate damping, the Rayleighmethod is used. In this method, the damping matrix is considering as the linear summation of the mass and stiffness matrices:

$[C] = \alpha\,[M] + \beta\,[K]$ (3)
So the damping value in natural modes is obtained from the following equation:
$\xi_n = \frac{\alpha}{2\,\omega n} + \frac{\beta\,\omega n}{2}$(4)
Where $\xi$ = Rayleigh Damping of the whole system, α, β = damping coefficients and w= natural frequencies of the system.

### 2.3. Modeling nonlinear BEHAVIOR OF MATERIALS

The CDP (concrete damage plasticity) constitutive modelin ABAQUS softwareis able to model the concrete and other quasi-brittle materials in all types structures. This model uses the concepts of Isotropic damaged elasticity with isotropic compressive and tensile plasticity to express nonlinear concrete behavior. This model consists of combination of nonassociated multi-hardening plasticity and scaler damage elasticity to describe theunrecovered failure that occurs during fracture processes and can be defined as sensitive to strain rate changes.

### 2.4. Nonlinear behavior of brittle and quasi-brittle materials

Brittle and quasi-brittle materials such as unreinforced concrete and CMD materials are disposed to cracking. ByRankin failure criterion if the maximum tensile stress in any point of material exceeds its tensile strength, the concrete will crack. The direction of this The direction of this cracking is perpendicular to the maximum stress direction. Post-failure behavior is modeled for direct strain with tensile stiffness, which allows to define the strain softening behavior of cracked materials.

### 2.5. Stress-strain relation after fracture

The cracking strain is the total strain minus the elastic strain corresponding to the non-cracked material. It means:

$\tilde{\varepsilon}_t^{ck} = \varepsilon_t - \varepsilon_{0t}^{el}$ (5)

Where:

$\varepsilon_{0t}^{el} = \sigma_t / E_0$ (6)

The tensile strength data must be determined according to cracking strain, $\tilde{\varepsilon}_t^{ck}$. When unloading information is available, this information should be provided in terms of tensile failure diagrams $d_t$ -$\tilde{\varepsilon}$ tck as will be explained below.Abaqus automatically converts cracking strain to equivalent plastic strain values in Equation No. 7:

$$\tilde{\varepsilon}_t^{pl} = \tilde{\varepsilon}_t^{ck} - \frac{dt}{(1-dt)}\frac{\sigma t}{E0} \qquad (7)$$

### 2.6. MODELLING THE RESEVOIR OF DAM

The only degree of freedom in the dam reservoir is the dynamic pressure value in the finite element model nodes of the reservoir. In Abaqus, acoustic materialhas this property and is suitable for dam reservoir modeling.[4].Acoustic material is capable of modeling compression wave transfer in an environment such as a dam reservoir.

The acoustic environment is an elastic (usually fluid) environment in which there is no shear stress and the pressure is proportional to the volume strain.Elastic properties of water materials include density of 1000 kg / m3 and bulk modulus of 2.27 Gpa.

## 3. NONLINEAR SEISMIC SIMULATION OF TOBETSU DAM

The Tobetsu Dam is a trapezoidal-shaped cement dam with an approximate height of 52 meters and a base width of about 92 meters located in the middle of the Tobetsu River in Japan (figure 1). In this analysis, seismic analysis of this dam was carried out under 6 horizontal earthquake records with different frequency contents but equal duration and PGA.hydrodynamic effects and dam-reservoir interaction is considered.The categorization of the records is based on a ratio of PGA/PGV, which according to the technical literature indicates the frequency content.A ratio greater than 1.2 means "earthquake with high frequency content", between 0.8 and 1.2means "earthquake with intermediate frequency content" and less than 0.8 means"earthquake with low frequency content". (according to naumoski's suggestion)[7]. From each category listed, two records fromnatural and recorded earthquakes are selected.The general characteristics of the selected earthquakes after scaling to 0.6g and considering the same duration are given in Table (1) and their response spectra in Figure (2).

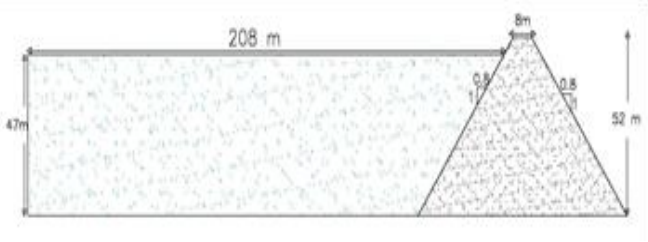


**Figure 1. Dimensions of Tobetsu dam and reservoir**

**Table 1- general characteristics of the selected earthquakes**

| NO | RECORD | YEAR | DURATION(S) | PGA(g) | PGV (cm/s) | A/V | FREQUENCY CONTENT CLASSIFICTION |
|---|---|---|---|---|---|---|---|
| 1 | LONG BACH | 1933 | 10 | 0.6g | 142.85 | 0.42 | Low |
| 2 | SAN FERNANDO | 1971 | 10 | 0.6g | 113.2 | 0.53 | Low |
| 3 | IMPRIAL VALLEY | 1940 | 10 | 0.6g | 57.14 | 1.05 | Intermediate |
| 4 | KERN COUNTY | 1952 | 10 | 0.6g | 57.1 | 1.05 | Intermediate |
| 5 | PARKFIELD | 1966 | 10 | 0.6g | 31.25 | 1.92 | High |
| 6 | HELENA | 1935 | 10 | 0.6g | 29.55 | 2.03 | High |

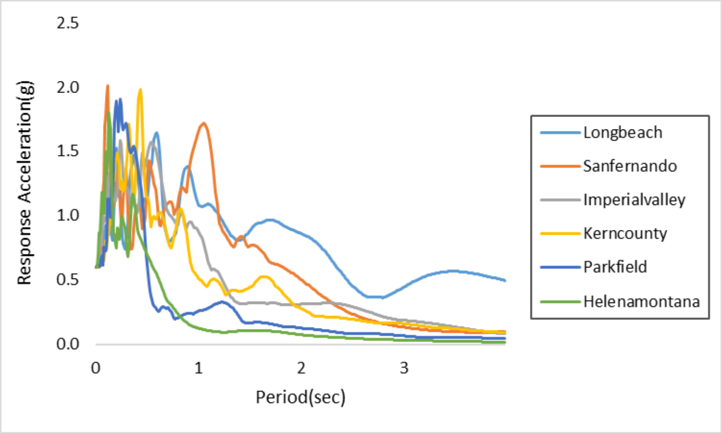


**Figure 2.** response spectra of the selected earthquakes

The behavior of elastic zone of CMD is considered with density value of 1900 kg / m3, Young modulus of 2 GPa and Poisson's ratio of 0.3. [5] & [6].Due to quasi-brittle nature of the CMD materials, for modelling the nonlinear behavior of this material we chooseCDP (concrete damage plasticity) approach. [8]

The characteristics of the plastic area of CMD materials can be found in Table (2).The stress-strain curve of cracking was used to define the tensile behavior of CMD material in the nonlinear area.Figure (3).

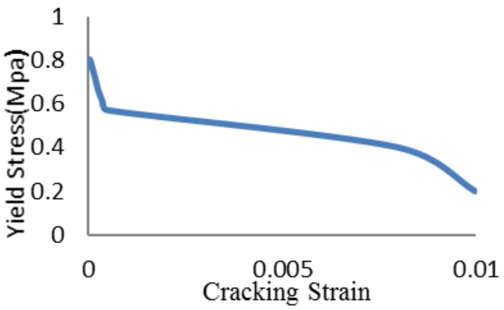
**Table 2- characteristics of the plastic area of CMD material**

| plastic specification | |
|---|---|
| type | Concrete damaged plasticity |
| Dilation Angle | 15 |
| Eccentricity | 0.1 |
| fb0/fc0 | 1.16 |
| K | 0.666 |
| Viscosity Parameter | 0 |

### 3.1. determining tension damage variable

To determine the values of tension damage variable, we obtain a value of zero for the values of plastic strain in formula (7) and formula (8) is achieved to calculate the values of maximum tension damage variable values. As we can see in figure (4).

$$dt = \frac{E_0 \varepsilon_t^{ck}}{\sigma_t + E_0 \varepsilon_t^{ck}} \tag{8}$$



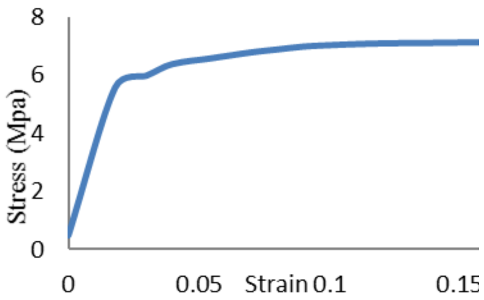
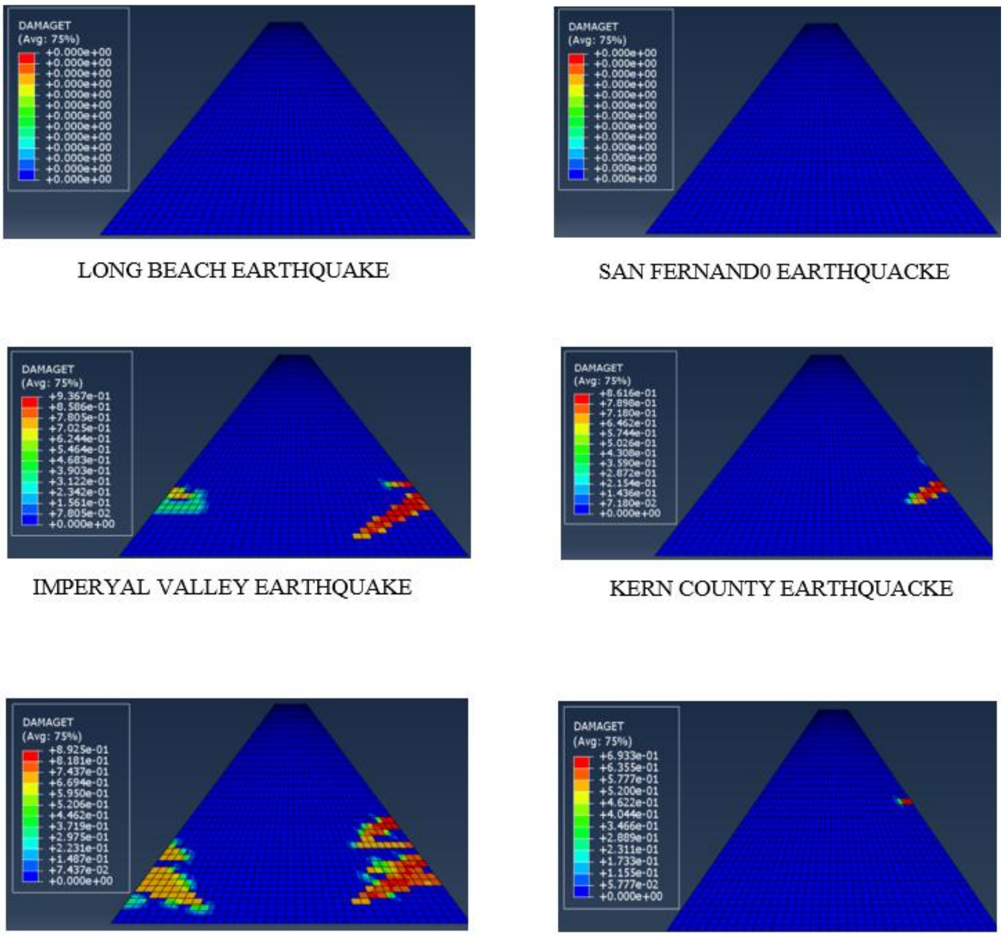


**Figure 3. the stress-strain curve of crackingFigure 4. t values of maximum tension damage**

## 4. ANALYSIS RESULTS

The results of the nonlinear analysis of the Tobetsu Dam subjected to selected earthquakes are presented below including cracking profiles of the dam.Then, by studying the frequency content of each earthquake, we try to find the effective factor in the rate of cracking.



LONG BEACH EARTHQUAKE

SAN FERNAND0 EARTHQUACKE

IMPERYAL VALLEY EARTHQUAKE

KERN COUNTY EARTHQUACKE

PARKFIELD EARTHQUACKE

HELENA MONTANA EARTHQUACK

**Figure 5. cracking profiles of the dam**

By defining “Damage index” as a ratio of cracked area of dam body to its total area, andregarding the cracking profiles, it can be seen that the damage index rate is generally increased with increasing the index of frequency content (PGA/PGV).As in the San Fernando and Long Beach earthquakes with low frequency content index, no damage is seen in the dam body.But as can be seen, this trend is not certain, as in the Imperial valley earthquake with the frequency content index (PGA/PGV = 0.82) the damage index is much greater than the Helena Montana earthquake with the frequency content index (PGA/PGV = 2.03).The Imperial Valley earthquake is in the intermediate frequency range and the Hanna Montana earthquake is in the high frequency range.Since the frequency content of earthquakes is reflected in the Fourier spectrum and the response spectrum of the earthquake, the Fourier spectra graphs and the responses spectra of acceleration of the earthquakes response are examined.

## 4.1. Fourier spectrum investigation

Fig. 6 shows the Fourier spectra graphs of earthquakes with the location of the natural frequency of the Tobetsu Dam(fn).For comparison, Fourier spectra graphs of earthquakes with the same category are shown in one graph.Modal analysis was performed in the Abaqus program to extract the natural frequency ofTobetsu Dam.The first mode frequency for Tobetsu Dam is 3.7 Hz, which represents the natural frequency of it.

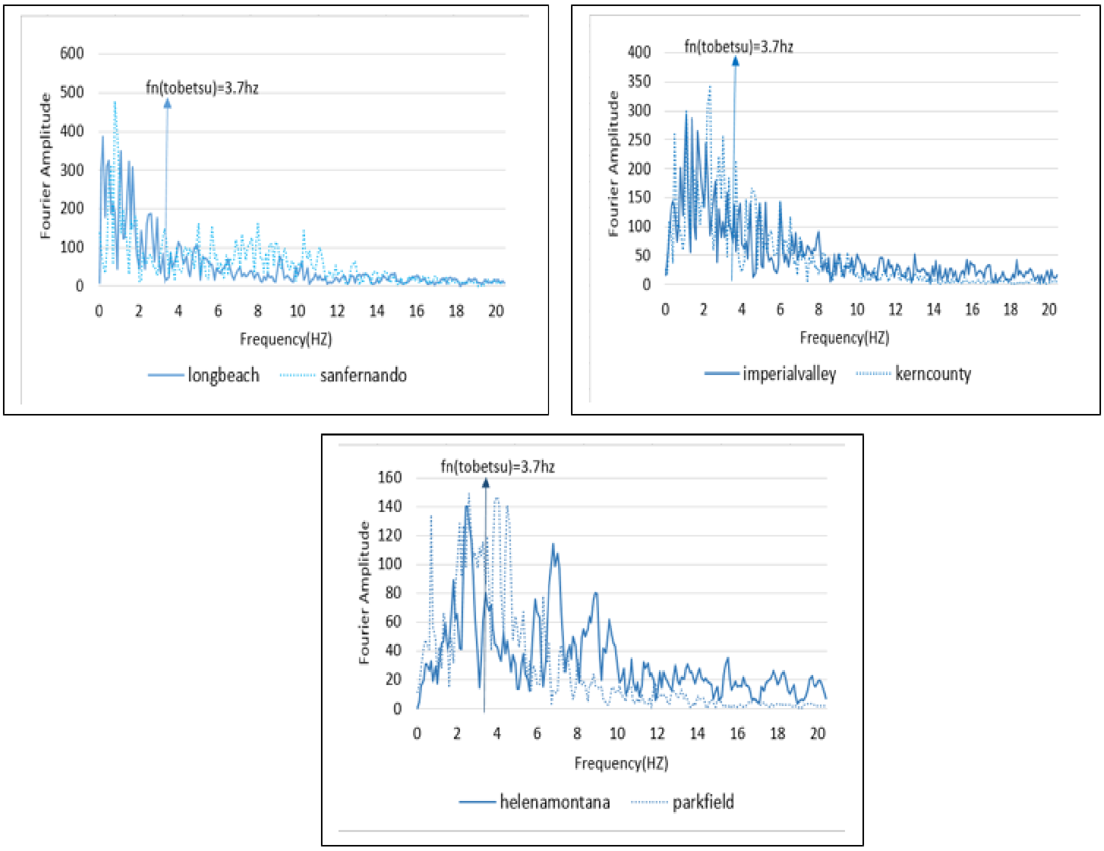


**Figure 6.Fourier spectra graphs of earthquakes**

By regarding theFourier spectra graphs of earthquakes, In the Fourier spectra graphs of the San Fernando and Long Beach earthquakes, the natural frequency of the CMD dam is within the range of the low amplitudes, which can be the reason for these earthquakesto be nondestructive.in the case of Park field earthquake with the highest volume of destruction (12.7%), the natural frequency of the dam is found in the high frequency range.

## 4.2. Responses spectra of acceleration investigation

On the response spectrum of each earthquake, the location of the dam's natural frequency (fn) and the location of the earthquake's predominant frequency (fp) and their corresponding acceleration were determined. A parameter is defined as the “response acceleration ratio” which is the ratio of the response acceleration at natural frequency to the response acceleration at the predominant frequency for each earthquake. The following diagram (Figure 6) shows the damage index of the Tobetsu Dam body under each earthquake based on this parameter. This diagram shows that damage index is greater when this parameter is increased.

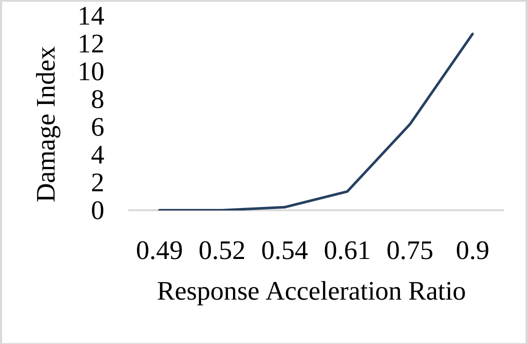


**Figure 7.damage index graph**

## 5. CONCLUSION

The results of this study show that the frequency content of input motion affects the damage index of the body of the Tobetsu as a CMD dam.

It has been seen that the increase in damage index for the Tobetsu dam, which is a case study of CMD dams, does not always depend on the increase in the frequency content parameter index. As in the Helena Montana earthquake with the maximum frequency content index of 2.02, damage index is less than others.By regarding the response spectrum graph, it was found that the natural frequency location of the CMD dam on it is an important factor in thedamage indexrate.The percentage of damage index increased by increasing the“response acceleration ratio “parameter.

From this research it can be concluded that the frequencies in an earthquake spectrum are a very important factor in impact on a CMD dam.The frequency contentof an earthquake appears in the Fourier spectrum graphs and the responses spectrum.Therefore, calculating the natural frequency of the dam and finding its location on the mentioned spectrums, can partly indicate the severity of an earthquake's impact on that dam.

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