0334

DETERMINATION OF DYNAMIC PROPERTIES OF EXISTING CONCRETE GRAVITY DAM BASED ON ACTUAL EARTHQUAKE MOTIONS

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SUMMARY

The results of seismic stability analysis of concrete gravity dam largely change according to the assumption of the dynamic property values of dam and foundation. Therefor, it is necessary to make the dynamic property values of dam and foundation clear, in order to improve the accuracy and the reliability of dynamic analysis. In this paper, the dynamic shear modulus and the damping factor of the existing concrete gravity dam were determined based on the backward analyses of the actual earthquake response. At the Kushiro-oki Earthquake of magnitude 7.8, on 15 January 1993, the maximum accelerations of 28.7gal occurred at the dam bottom gallery, and 77.3gal occurred at the dam crest were observed at the existing concrete gravity dam constructed in 1956 in Hokkaido. In regard to this earthquake event, 2-D and 3-D FEM dynamic analyses were carried out to reproduce the earthquake behavior of the dam. Four kinds of FEM models, namely the 2-D dam body model, the 2-D dam-foundation model with reflective boundary, the 2-D dam-foundation model with non-reflective boundary, and the 3-D dam-foundation-reservoir model with non-reflective boundary were used. As the results, the dynamic shear modulus of the dam was evaluated to be 11,032(N/mm^2). The material damping factor of the dam and the foundation was evaluated to be 5%. The radiation damping factor was evaluated according to the boundary conditions and the dynamic interactions between the dam and the foundation.

INTRODUCTION

In the seismic stability analysis of concrete gravity dam with the dynamic analysis method, the solutions of dynamic stress and strain of the dam body during earthquake largely change depending on the assumption of the dynamic properties of dam and foundation. In particular the assumption of the dynamic shear modulus and the damping factor of the dam- foundation system have significant effects on not only the acceleration response but also the dynamic tensile stress and strain of the dam body. Therefore, in order to execute an accurate and reliable dynamic analysis for concrete gravity dam, it is necessary to estimate the dynamic properties of dam and foundation appropriately.

The physical properties of dam materials are generally investigated and evaluated by the laboratory tests. However, the studies on the dynamic deformation properties by the laboratory tests are relatively few. Furthermore, the studies for verifying the validity of the property values evaluated by the laboratory tests are even less, and there are still many

problems unsolved. According to such a necessity, 2-D and 3-D FEM dynamic analyses were carried out in order to reproduce the earthquake behavior of a real concrete gravity dam during the actual earthquake. As the results, its dynamic shear modulus and damping factor were evaluated. It is expected that the results are informative for the numerical analyses of other dams.

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EARTHQUAKE OBSERVATION AT EXISTING CONCRETE GRAVITY DAM

The object for reproduce analysis is the existing concrete gravity dam of 76m in height, 273m in crest length, constructed in 1956 in the central part of Hokkaido. The location of the dam is shown in Fig.-1. The foundation rock at the dam site is the andesite ,which is very hard itself but contains many irregular cracks. The thickness of the andesite is 10m~20m. Below the andesite, the alternation of strata with the tuffaceous sandstone and the tuffaceous shale is distributed. This alternation of strata is softer compared with the andesite.

The location of seismometers is shown in Fig. -2. The seismometers are installed at three points, that is the dam crest, the dam bottom gallery, and the right rock abutment. The earthquake observation has been carried out since 1983 continuously.

Earthquake Event to be analyzed

The earthquake event analyzed in this study is the Kushiro-oki Earthquake of magnitude 7.8 , which occurred on 15 Jan. 1993. The Kushiro-oki Earthquake(1993) is well-known as the intraplate earthquake . The epicenter is lat.42°51'N and long.144°23'E. The focal depth is 107km. The epicentral distance and the hypocentral distance at the dam site are 110km and 153km respectively. The outline of the earthquake observation results at the Kushiro-oki earthquake is shown in Table-1.

The observed maximum acceleration was 77.4gal at the dam crest, 28.7gal at the dam bottom gallery, and 34.7gal at the right rock abutment. The magnification of acceleration response (Dam crest/Dam bottom gallery) in the up-down stream direction was 2.8. And the magnification of acceleration response (Right Rock Abutment/Dam bottom gallery) in the up-down stream direction was 1.04. The amplification of the foundation rock was smaller than that of the dam body.

Comparing the up-down stream direction with the dam-axis direction, the maximum acceleration at the dam crest in the up-down stream direction was 77.4gal, and 42.6gal in the dam-axis direction. The maximum acceleration at the dam bottom gallery in the up-down stream direction was 27.5gal, and 28.7gal in the dam-axis direction. The maximum acceleration at the right rock abutment in the up-down stream direction was 28.7gal and 34.7gal in the dam-axis direction. In regard to the dam body, the amplification in the up-down stream direction was much larger than that in the dam-axis direction. On the other hand, there was almost no difference between the amplification in the up-down stream direction and that in the dam-axis direction in regard to the dam bottom gallery and the right rock abutment.

Comparing the horizontal motions with the vertical motions, the acceleration of the vertical motion was about one forth of that of the horizontal motion in the up-down direction at the dam crest , and about one second in the dam-axis direction. At the dam bottom gallery and the right rock abutment, the vertical motions were about one second of the horizontal motions.

The predominant frequency of the transfer function between the dam crest and the dam bottom gallery, or the natural frequency of the dam was approximately 5.2Hz (in the up-down stream direction). The acceleration time histories observed at the dam crest and at the dam bottom gallery, and the transfer function between the dam crest and the dam bottom gallery are shown in Fig-3.

DYNAMIC ANALYSIS FOR REPRODUCING REAL EATHQUAKE BEHAVIOR

2-D and 3-D FEM dynamic analyses were carried out in order to reproduce the earthquake behavior of existing concrete gravity dam during the Kushiro-oki Earthquake. This reproduce analyses were carried out by paying attention to the maximum amplitude of the response motion at the dam crest and the predominant frequency of the transfer function between the dam crest and the dam bottom gallery. The property values of the dynamic shear modulus and the damping factor were decided to agree between the observed results and the analyzed results regarding the maximum amplitude of response motion and the predominant frequency of transfer function. For 2-D FEM dynamic analyses the analysis program"Super FLUSH" was used. And the 3-D FEM dynamic analyses were done by using the 3-D dam-foundation-reservoir system dynamic analysis program "UNIVERSE", which is developed by the authors.

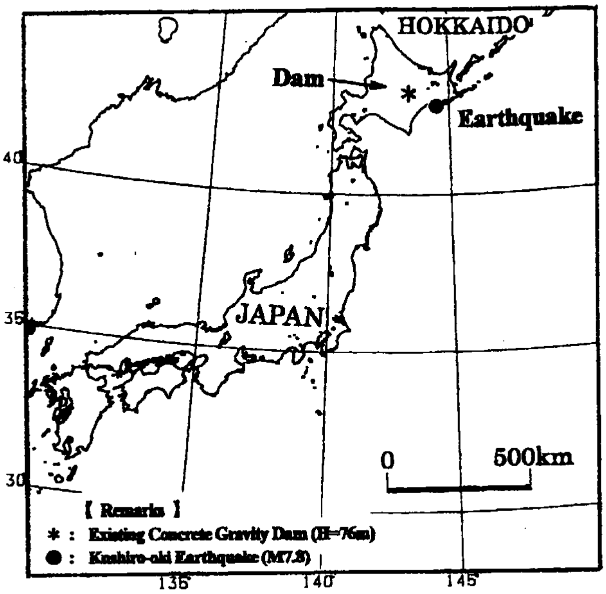


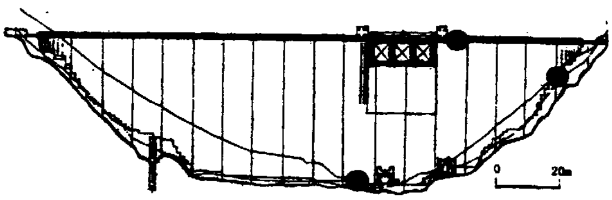
Fig.-1 Location of Existing Concrete Gravity Dam and Kushiro-oki Earthquake (M7.8, Jan.15th 1993)

Table-1 Earthquake Observation Results at Existing Concrete Gravity Dam during The Kushiro-oki Earthquake

KUSHIRO-OKI EARTHQAUKE		
Date		Jan. 15. 1993
Epicenter		Lat.42° 15'N Long.144° 22'E
Magnitude		7.8
Focal Depth		107km
Epicentral Distance		110km
Hypocentral Distance		153km
MAXIMUM ACCELERATION		
Dam Crest	STR	77.4gal
	AXI	42.6gal
	U-D	19.8gal
Dam Bottom Gallery	STR	27.5gal
	AXI	28.7gal
	U-D	14.7gal
Right Rock Abutment	STR	28.7gal
	AXI	34.7gal
	U-D	18.1gal
Natural Frequency		5.2Hz

【Note】 STR : Horizontal Up-down Stream Direction
AXI : Horizontal Dam-Axis Direction
U-D : Vertical Direction

Crest Length : 273m

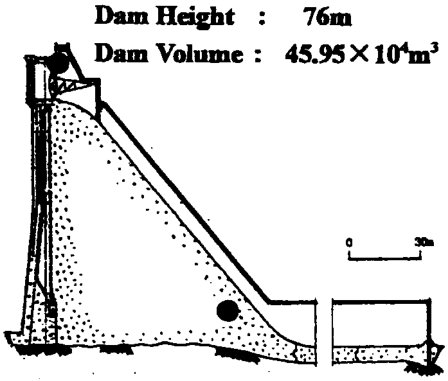


Dam Height : 76m

● : Seismometers

(1) Down Stream View

Crest Length : 273m
Dam Height : 76m
Dam Volume : 45.95×10⁴m³



● : Seismometers

(2) Typical Cross Section

Fig.-2 Shape of Existing Concrete Gravity Dam and Arrangement of Seismometer

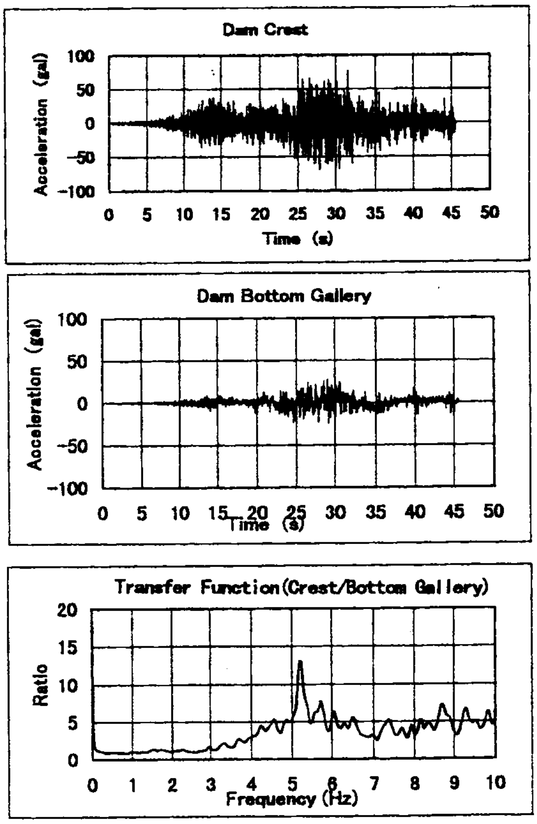


Fig.-3 Observed Earthquake Motions at the Kushiro-oki Earthquake and Transfer Function

Dynamic Analysis Model

Four kinds of dynamic analysis models, namely (1) 2-D dam body analysis model with reflective boundary, (2) 2-D dam-foundation system analysis model with reflective boundary, (3) 2-D dam-foundation system analysis model with non-reflective boundary, (4) 3-D dam-foundation-reservoir system analysis model with non-reflective boundary, were used in this study in order to investigate the effects of dynamic interaction between dam and foundation, the effects of reservoir, the effects of boundary conditions, the three dimensional effects, and the values of damping factor .

2-D Dam Body Analysis Model

The 2-D dam body analysis model is shown in Fig.-4. The rigid boundary is applied as the basal boundary. The node number is 183, and the element number is 163.

2-D Dam-Foundation System Analysis Mode with Reflective Boundary

The 2-D dam-foundation system analysis model with the horizontal roller support as the side boundary and the rigid boundary as the basal boundary is shown in Fig.-5. The foundation rock domain is 600m in width and 300m in depth. The node number is 1,089, and the element number is 1,035.

2-D Dam-Foundation System Analysis Model with Non-reflective Boundary

The 2-D dam-foundation system analysis model with the energy transmitting boundary as the side boundary and the viscous boundary as the basal boundary is shown in Fig.6. The FEM mesh is same as Fig.5.

3-D Dam-Foundation-Reservoir System Analysis Model with Non-reflective Boundary

The 3-D dam-foundation-reservoir system analysis model with the viscous boundary as the side boundary and the rigid boundary as the basal boundary is shown in Fig.7. The 8-nodes solid elements were used for the dam body and foundation. The node number is 3,494, and the element number is 2,801. The differential grids were used for the reservoir. The grid number is 3,670.

Dynamic Property Values

The dynamic property values of dam and foundation used in the analyses are shown in Table-

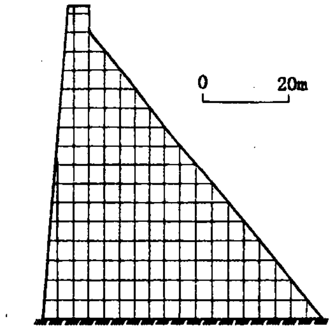


Fig.-4 2-D Dam Body Model

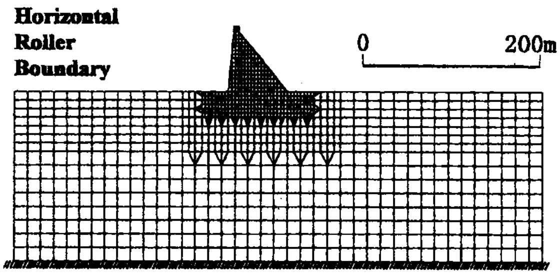


Fig.-5 2-D Dam-Foundation System Model with Reflective Boundary

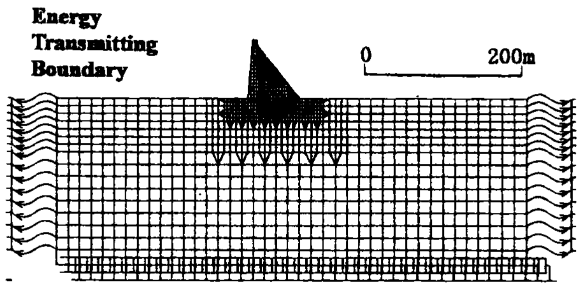


Fig.-6 2-D Dam-Foundation System Model with Non-reflective Boundary

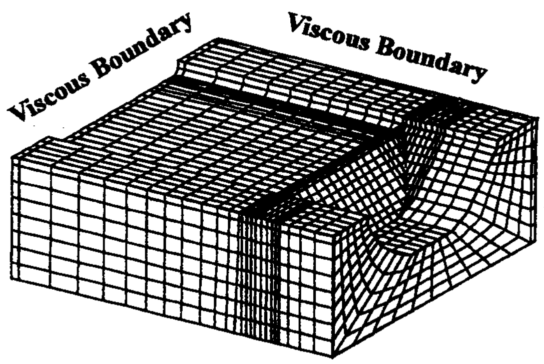


Fig.-7 3-D Dam-Foundation-Reservoir System Model with Non-reflective Boundary

2. The density was assumed with reference to the test results carried out at the time of dam construction. The dynamic poisson's ratio was assumed with reference to the values generally applied. The value of dynamic shear modulus of the dam was decided according to the results of 2-D dam body analysis by the back-analytical approach. The value of dynamic shear modulus of the dam was commonly used to the four kinds of analysis models. The values of damping factor were decided to agree between the observed results and the analysis results. The values of damping factor for the dam and the foundation are assumed in the range of 5%~20 %. The shear wave velocity was calculated from the density and the dynamic shear modulus.

Table-2 Dynamic Property Values for Analyses

ITEMS	VALUES
【DAM BODY】	
Density	2.4 (t/m^3)
Dynamic Shear Modulus	11,032 (N/mm^2)
Dynamic Poisson's Ratio	0.2
Damping Factor	5～20(%)
Shear Wave Velocity	2140 (m/s)
【FOUNDATION ROCK】	
Density	2.6 (t/m^3)
Dynamic Shear Modulus	9,380 (N/mm^2)
Dynamic Poisson's Ratio	0.3
Damping Factor	5～15 (%)
Shear Wave Velocity	2059 (m/s)

Earthquake Input

In the case of the 2-D dam body analysis, the observed earthquake motion at the dam bottom gallery was input directly from the input base. In the cases of the 2-D dam- foundation system analysis and the 3-D dam-foundation

system analysis, the input earthquake motion at the basal boundary was generated by transferring the observed earthquake motion at the dam bottom gallery. During this process, the dynamic interaction between the dam and the foundation was taken into account. The whole earthquake motion was used in 2-D analysis, or the duration time of input motion is 46sec. In this case, the horizontal motion in the up-down stream direction and the vertical motion were input simultaneously. In the 3-D analysis, the 20.24sec-section of earthquake motion ,between 18.05~38.29sec was used, and three components of motion, that is the horizontal up-down stream direction, the horizontal dam-axis direction, and the vertical direction, were input simultaneously.

Table-3 Results of Reproduce Analysis regarding Earthquake Behavior of Existing Concrete Gravity Dam

ITEMS	Real Earthquake Observation Results	2-D Dam Body Model	2-D Dam-Foundation Model (Reflective Boundary)	2-D Dam-Foundation Model (Non-reflective Boundary)	3-D Dam-Foundation -Reservoir Model (Non-reflective Boundary)
DAM BODY					
Density (t/m^3)		2.4	2.4	2.4	2.4
Dynamic Shear Modulus (N/mm^2)		11,032	11,032	11,032	11,032
Damping Factor (%)		20	10	10	5
Shear Wave Velocity (m/s)		2,140	2,140	2,140	2,140
FOUNDATION ROCK					
Density (t/m^3)			2.6	2.6	2.6
Dynamic Shear Modulus (N/mm^2)			9,380	9,380	9,380
Damping Factor (%)			15	10	5
Shear Wave Velocity (m/s)			2,059	2,059	2,059
MAX. ACC. at Dam Crest (Up-Down Stream Direction)	77.4gal	74.3gal	98.4gal	99.6gal	80.gal
MAX.ACC. at Dam Bottom Gallery (Up-Down Stream Direction)	27.5gal	26.8gal	24.6gal	25.1gal	28.0gal
ACC. Response Ratio (Dam Crest/Dam Bottom Gallery)	2.9	2.8	4.0	4.0	2.9
Natural Frequency (Up-Down Stream Direction)	5.2Hz	5.2Hz	3.7Hz	3.8Hz	5.2Hz

Modeling of Reservoir Water

In the 2-D analysis, the reservoir water was treated as the added mass. In the 3-D analysis, the reservoir water was treated as wave motion problem and its equation was formulated with the finite difference method.

Analyzed Results

The earthquake observation results, the 2-D and the 3-D analysis results are summarized in Table-3.
The comparison of the observed result and the analyzed results about the acceleration time-history at the dam crest is shown in Fig.-8. Similarly, the comparrison about the transfer function between the dam crest and the dam bottom gallery in shown in Fig.-9.

In the 2-D dam body analysis, the dynamic shear modulus of dam was first evaluated to be in agreement regarding the predominant frequency of transfer function. Secondary, the damping factor was evaluated to be in agreement regarding the maximum acceleration of motion at the dam crest.

As for the 2-D dam body analysis, the following relationship exists between the dynamic shear modulus and the predominant frequency of transfer function.

$$Ga : Gb = F a^2 : F b^2$$

Here,

Ga : Dynamic shear modulus assumed in the analysis Case A
Gb : Dynamic shear modulus assumed in the analysis Case B
Fa : Predominant frequency of transfer function of Case A
Fb : Predominant frequency of transfer function of Case B

The dynamic shear modulus could easily be evaluated by utilizing this relationship. The 2-D dam body analysis is considered to be an effective approach for evaluating the natural frequency of dam or the dynamic shear modulus . On the other hand, this approach is not appropriate for evaluating the damping factor because of the significant effects of the boundary. The damping factor evaluated by this approach is considered to include the material damping and the radiation damping . As the results of the2-D dam body analysis, the dynamic shear modulus of the dam was estimated to be 11,032(N/mm^2) , the total damping factor to be 20%.

In the 2-D dam-foundation system analysis, the influence of the boundary, or the difference between the analysis with the reflective boundary and the analysis with the non-reflective boundary, is very clear regarding the maximum acceleration of motions, but not clear regarding the frequency characteristics of motions. In comparison with the2-D dam body analysis and the 2-D dam-foundation system analysis, it is remarkable that the analytical treatment of the foundation rock considerably affects on the transfer function.. The 2-D dam-foundation system analysis is considered to be an effective approach for the dam site where the foundation rock is harder than the dam body. To the contrary, for the dam site where the foundation rock is softer than the dam body, careful attention must be paid to the results by this approach.

In the 3-D dam-foundation-reservoir system analysis, the analyzed results agree with the observed results very well when the dynamic shear modulus was assumed to be 11,032(N/mm^2) , and the damping factor to be 5 % for the dam and the foundation .

CONCLUSIONS

Relationship between Dynamic Shear Modulus and Frequency Response

In the 2-D dam body analysis, the dynamic shear modulus could be easily evaluated to reproduce the predominant frequency of transfer function between the dam crest and the dam bottom gallery.

In the 2-D dam-foundation system analysis, it is to be noticed that the predominant frequency of transfer function changes according to the assumption of the dynamic shear modulus of foundation. When the dynamic shear modulus of foundation is greater than that of dam body, the predominant frequency of transfer function coincides with the natural frequency of dam. However, when the dynamic shear modulus of foundation is smaller than that of dam body, the predominant frequency of transfer function not necessarily coincides with the natural frequency of dam, because of the influence of the wave impedance ratio of dam body and foundation.

Relationship between Damping Factor and Acceleration Response

The damping factor directly affects the acceleration response of dam and foundation, on the other hand, hardly affects the frequency response. When the dynamic shear modulus of the foundation is greater than that of the dam body, the damping factor of the dam body controls the acceleration response. To the contrary, when the dynamic shear modulus of the dam is greater than that of the foundation, the damping factor of the foundation controls the acceleration response.

Evaluated Dynamic Shear Modulus and Damping Factor

In this study, the dynamic shear modulus of the existing concrete gravity dam during the Kushiro-oki Earthquake was evaluated to be 11,032(N/mm^2)
{the shear wave velocity 2,140(m/s)}, based on the

reproduce analyses. As for the damping factor, the material damping and the radiation damping was examined according to the comparative study of the 2-D and the 3-D FEM dynamic analyses. As the
results, the material damping factor was evaluated
to be 5 % regarding both the dam body and the foundation. The radiation damping factor regarding the dam body was evaluated to be 15 % in case of the 2-D dam body analysis, and to be 5 % in case of the 2-D dam-foundation system analysis. The radiation damping factor regarding the foundation was evaluated to be 10 % in case of the 2-D dam-foundation system analysis with the reflective boundary, and to be 5 % in case of the 2-D dam-foundation system analysis with the non-reflective boundary. In case of the 3-D dam-foundation-reservoir system analysis with non-reflective boundary, it was considered that the radiation damping of foundation is not necessary to be estimated in the analysis, because the radiation of
wave motion was considered analytically. The summarized results regarding the damping factor are shown in Table-4.
The analyses introduced in this paper were carried out by the linear dynamic analysis method, because the level of acceleration was not so large and the level of the dynamic shear strains was small. However, when the seismic stability evaluation of concrete gravity dam against very strong earthquake motion will be made , it will be necessary to carry out the non-linear dynamic analysis. In this case, how to assume the nonlinear properties of dam and foundation will became important. The non-linearity of the dynamic shear modulus and the damping factor is to be solved in the further study.

Table-4 Consideration on Damping Factor of Existing Concrete Gravity Dam and Foundation
(Tentative Consideration regarding Material Damping and Radiation Damping)

Analysis Model	Dam Body			Foundation Rock		
	D.F.	M.D.	R.D.	D.F.	M.D.	R.D.
2-D Dam Body Model (Rigid Boundary).	20	5	15	—	—	—
2-D Dam-Foundation Model (Reflective Boundary)	10	5	5	15	5	10
2-D Dam-Foundation Model (Non-reflective Boundary)	10	5	5	10	5	5
3-D Dam-Foundation-Reservoir Model(Non-reflective Boundary)	5	5	0	5	5	0

【Remarks】 D. F. : Total Damping Factor (%)
M. D. : Material Damping Factor (%)
R. D. : Radiation Damping Factor (%)

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