Vibration Analysis of Civil Structure

Koichiro Tada

Abstract: As considerable vibration and noise have been observed in particular places of the powerhouse of the Upper Kotmale Hydropower Project, site investigations and measurements of vibration in the powerhouse were carried out. Numerical analysis and study using collected data were also executed. As a result, long term stability of the Penstock and slab concrete against fatigue by the vibration are checked. It becomes clear that their improvements are not necessary and its future stability will be maintained.
Keywords: Vibration, Numerical Analysis, Powerhouse, Civil Structure

1. Introduction

As considerable vibration and noise have been observed in particular places of the powerhouse of the Upper Kotmale Hydropower Project, we carried out site investigation and measurement of vibration and noise (for reference) in the powerhouse.

Numerical analysis and study using collected data were also executed consecutively.

2. Method of Measurement

2.1 Measurement Devices

2.1.1 Vibration

Portable measurement device was used for measuring acceleration of vibration. Its specifications are shown in Table1, and their exterior view is shown in Fig.1.

Table 1 - Specifications of Vibration Analyser

Name	Model
Vibration Analyzer	VA-12 (RION CO., LTD.)
Piezoelectric Accelerometer (with magnet attachment)	PV-571 (RION CO., LTD.)
Measurement Range	
Acceleration	0.02 to 141.4m/s² (RMS)
Frequency	1Hz to 5kHz.

Figure 1 - Vibration Analyzer

2.1.2 Noise

For monitoring noise level in the powerhouse, portable sound level meter was used. Its specifications are shown in Table2, and their exterior view is shown in Fig.2.

Table 2 - Specifications of Sound Level Meter

Name	Model
Sound Level Meter	NL-22 (RION CO., LTD.)
Measurement Range	
A-weighted	28dB to 130dB

Figure 2 - Sound Level Meter

2.2 Setting of Measurement Devices

2.2.1 Vibration

For accurate measurement of acceleration level of the vibration, small metal attachments were fixed at the measuring points on the floor and wall using superglue.

The piezoelectric accelerometer was tightly fixed with the metal attachment by magnetic force during the measurement. Small metal attachments were prepared beforehand in Japan, and carried them to the site.

Detail shown in Fig.3.

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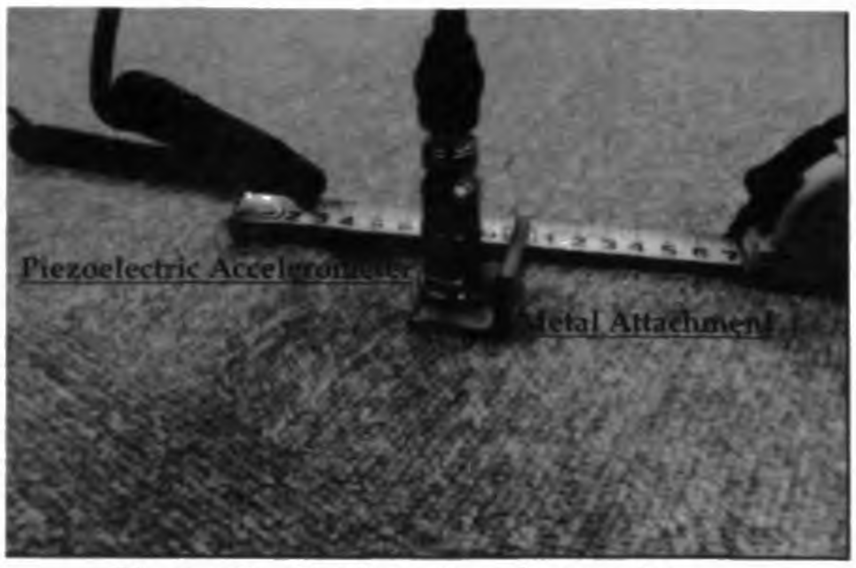


Figure 3 - Setting Accelerometer

Acceleration level data were recorded by vibration analyser and were saved to an attached SD card. Refer to Fig.4.
Monitoring range and time were as follows:
-Sampling Range : under 1,280Hz
-Vibration Data Sampling Time: 14.4sec

Figure 4 - Measuring Vibration

2.2.2 Noise

The sound level meter was fixed on a tripod. The indication of noise level was checked by visual observation of the indicator built in the meter.
Detail shows in Fig.5.

Figure 5 - Setting Sound Level Meter

2.3 Measurement Points

After checking actual condition of vibration and noise on-site, the measurement points were decided. We set measurement points on floor, wall and penstock.
Typical Section of Powerhouse shows in Fig.6.

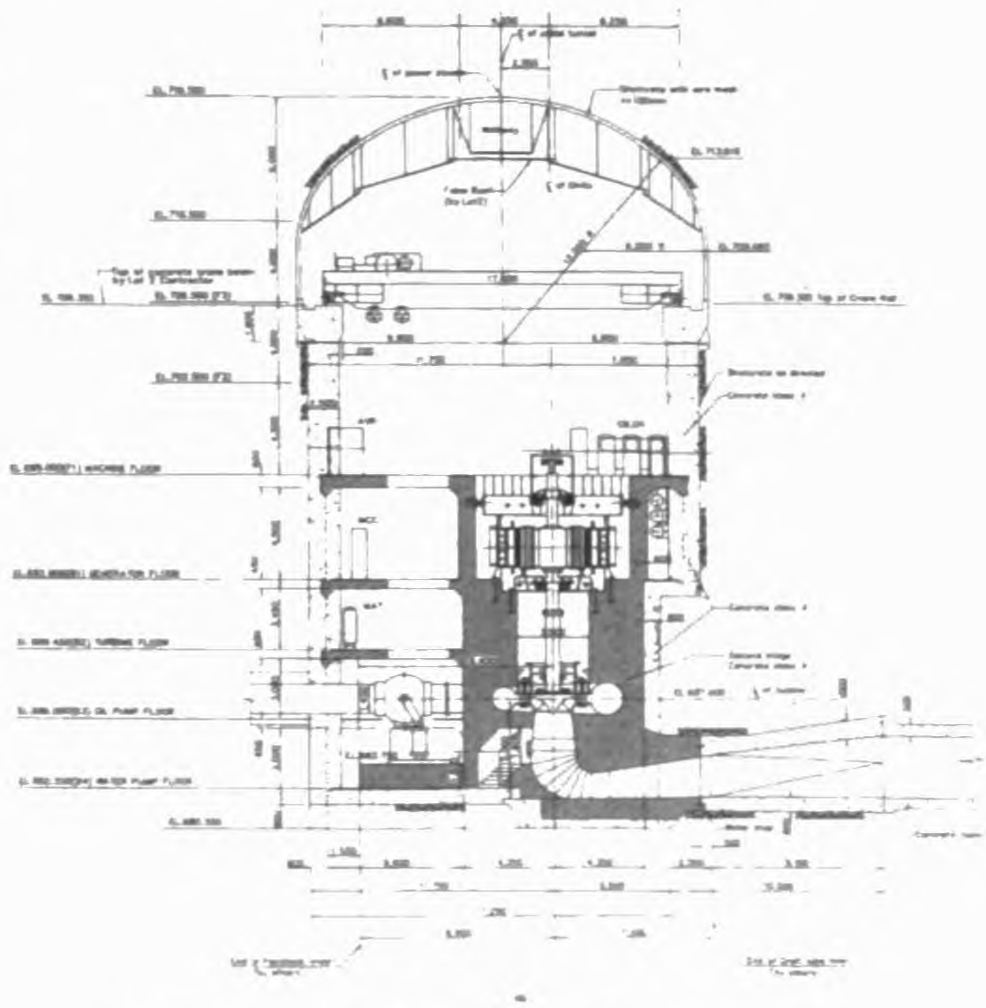


Figure 6- Typical Section of Powerhouse

Amount of measurement points show in Table3. An example of measurement points show in Fig.7 and Fig.8.

Table 3 - Amount of Measurement Points

Measurement Item		Amount
Vibration	Floor	31
	Wall	26
	Penstock	14
Noise		15

Figure 7 - Example of Vibration Measurement (Floor)

Figure 8 - Close Up

2.4 Timing of Measurement

Measurements of acceleration value were carried out during full load operation (75MW/unit) both unit 1 and unit 2.

3. Result of Measurement

3.1 Vibration

Maximum acceleration values of the powerhouse are shown in Table4.

Table 4 - Maximum Acceleration on Each Position

Position	Floor	Acceleration [RMS(m/s2)]	Dominant Frequency (Hz)
Floor	B2	6.01	180.6
Wall	B4	2.04	180.6
Penstock	B3	28.04	180.2

RMS (Root Mean Square) formula is as follows. The measured values are adapted to Xn.

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}$$

An example of Fourier Spectrum shows in Fig.8. Dominant frequencies are approximately 180Hz at all points.

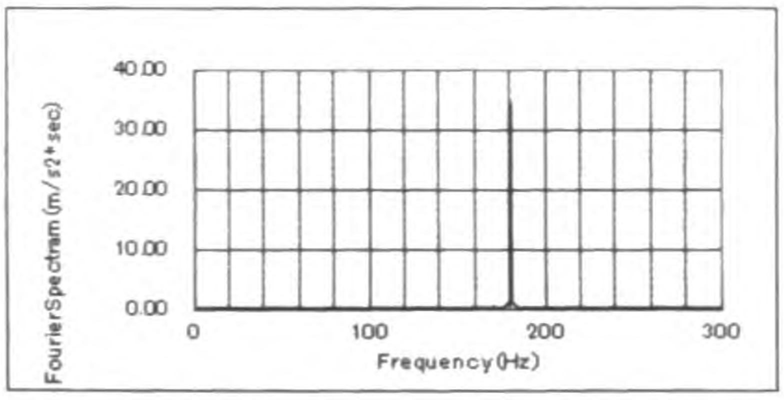


Figure 9 - Example of Fourier Spectrum (Floor B2)

Background accelerations at each measurement points are negligible level during shutdown of the both units. So vibration is caused by the generating operation.

3.2 Noise Level

Maximum noise level is 104 dB on B2 floor.
Almost all noise levels are over 85dB that is required level in the Specifications during full load operation.
Noise level on the B1 and F1 floor are little bit lower than that of other floors.
Background noise level is nearly 60 dB.

4. Numerical Analysis

4.1 Vibration in 180Hz

From the measurement data, 180Hz vibration is predominantly observed.
According to the previous and various researches, it is reported that turbine makes pulsatile water pressure in the Penstock. Pulsatile water pressure in the Penstock is never avoided to a varying degree and shows the frequency characteristics of three types as follows.

- Caused by the number of rotations of Turbine

  fw1=N/60 (1)

- Caused by the number of runner vanes

  fw2=NZ/60 (2)

- Caused by the whirl in Draft Tube

  fw3=N/(60*3.6) (3)

where
N: Number of rotations of Turbine (rounds per minutes)
Z: Number of runner vanes of Turbine
As N equals 600 and Z equals 18 on Upper Kotmale hydropower plant, fw1 is 10Hz, fw2 is 180Hz and fw3 is 2.78Hz. From this analysis, source of vibration in the Penstock is considered to be pulsatile water pressure caused by the number of runner vanes of the turbine, because 180Hz vibration is predominant.

4.2 Dominant Frequency of Penstock

Technical Standard for Gates and Penstock (Electric Power Civil Eng. Acc., Japan) shows Eq.(4) to estimate natural vibration frequency in case of simple penstock supports.

$$f = \frac{1}{2\pi r_m}\sqrt{\frac{E}{\rho}}\frac{1}{\sqrt{1+\frac{n^2}{n^2+1}\varepsilon}}\sqrt{\frac{n^2}{n^2+1}}\sqrt{\frac{\alpha^4}{\left(n^2+\alpha^2\right)^2}+\beta\frac{\left(n^2-1\right)^2}{1-\nu^2}+\frac{r_m P}{EI}\left(n^2-1\right)} \quad (4)$$

where
f : Natural vibration frequency of penstock
Es : Modulus of elasticity of steel
ρ s: Unit density of steel
vs : Poisson's ratio of steel
t : Thickness of penstock
rm : Radius of penstock
L : Span of penstock

P: Water pressure
n: Mode number in the direction of circumference
k: Mode number in the direction of penstock axis
ε: (Unit density of water / Unit density of steel)×rm/(t×n)

$$\alpha = k\pi r_m / L, \quad \beta = t^2 / 12 r_m^2$$

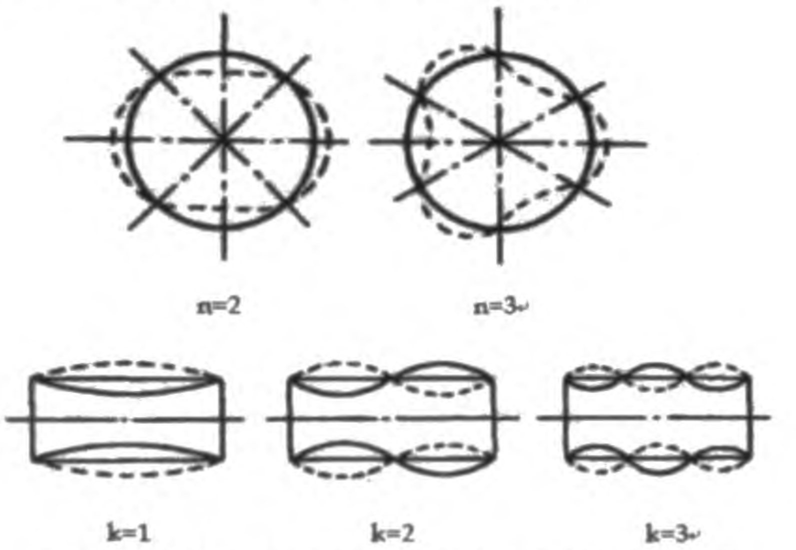


Figure 10 - Mode Number of Penstock

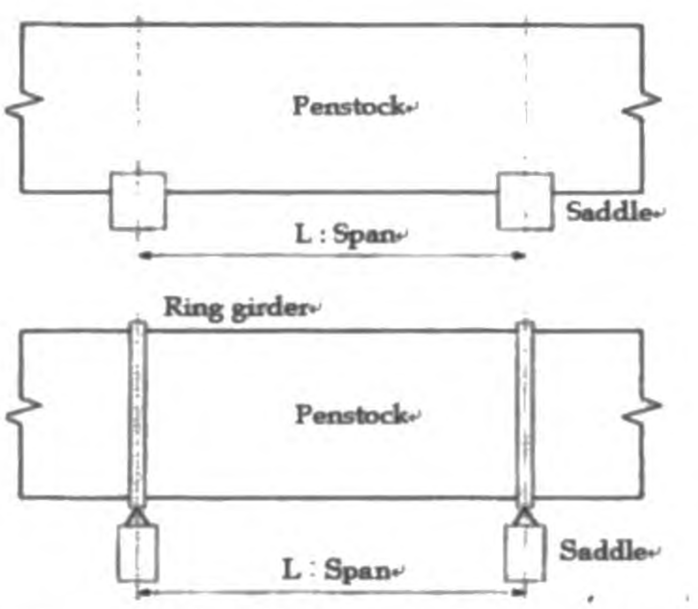


Figure 11 - Model Span of Penstock

Though there are some differences for penstock support between condition of Eq.(4) and actual complicated structure (Fig.12), the natural vibration frequency of the Penstock is estimated for reference. Results of calculation are shown in Table.5. From result, there are some possibilities that the Penstock resonance is affected by pulsatile water pressure in 180 Hz.

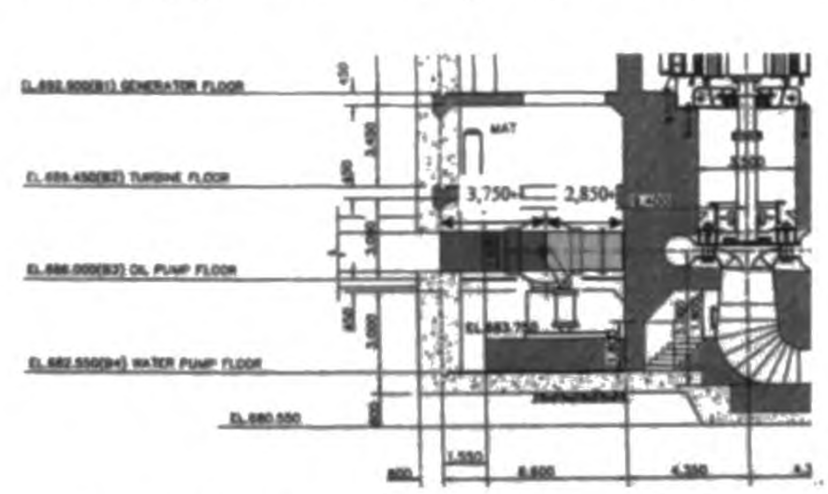


Figure12 - Assumption when applying the Eq.(4)

Table5- Natural Vibration Frequency of Penstock based on Eq.(4)

L=2,850(mm)				
	k=1	k=2	k=3	k=4...
n=2	95 Hz	251 Hz	375 Hz	·
n=3	94 Hz	**182 Hz**	297 Hz	·
n=4	148 Hz	**182 Hz**	256 Hz	·
n=5	231 Hz	243 Hz	279 Hz	·
n=6...	·	·	·	·
L=3,750(mm)				
	k=1	k=2	k=3	k=4...
n=2	64 Hz	**176 Hz**	291 Hz	·
n=3	85 Hz	131 Hz	214 Hz	·
n=4	146 Hz	160 Hz	200 Hz	·
n=5	230 Hz	235 Hz	251 Hz	·
n=6...	·	·	·	·

4.3 Dominant Frequency of Powerhouse

4.3.1 Introduction

According to the results of measurements, it seems that turbine makes vibration and noise in 180 Hz as some resonance phenomena.

An Eigenvalue analysis was carried out to compare with the measurements result.

4.3.2 Analysis Condition

In order to know resonance frequencies of floors, Eigenvalue analyses are carried out for the B2 floors of the Upper Kotmale Hydro Powerhouse.

Analyses ranges are shown in from Fig.13 to Fig.14.

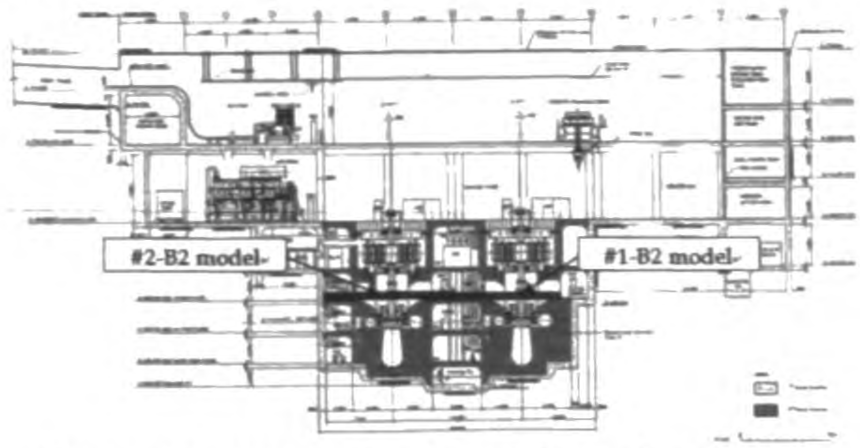


Figure 13 - Cross Section of Powerhouse

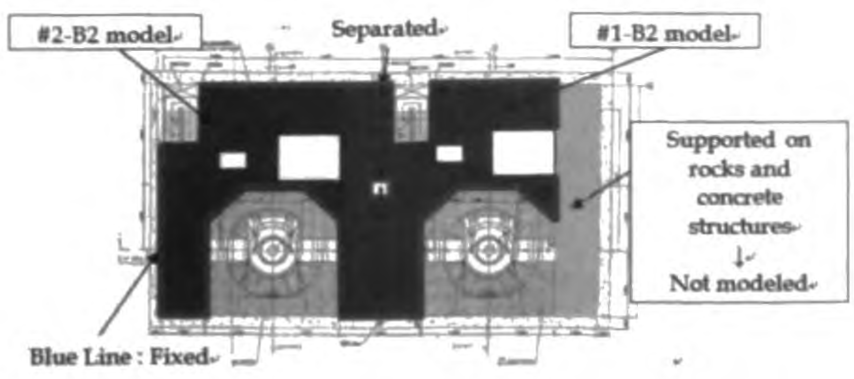


Figure 14 -Plane chart of the powerhouse (B2 floor)

Material properties of reinforced concrete are shown in Table6, which are used in the design. Analysis models are composed of shell elements, and boundaries are fixed between at walls. Analysis code MD/NASTRAN is used.

Table.6 Material Properties of Concrete

Unit Weight	25 (kN/m^3)
Modulus of Elasticity	27 (kN/mm^2)
Poisson's Ratio	0.17

4.3.3 Result

The result of the analyses shows in Fig.15.
Resonance frequency is in around 170Hz on the Unit2 B2 floor in 23rd mode.
It is similar to actual vibration. Resonance frequencies of the analyses of 170Hz are different from the measurements of 180Hz. This reason is considered that material property (especially for modulus of elasticity) and boundary condition are a little bit different between those for design and actual.

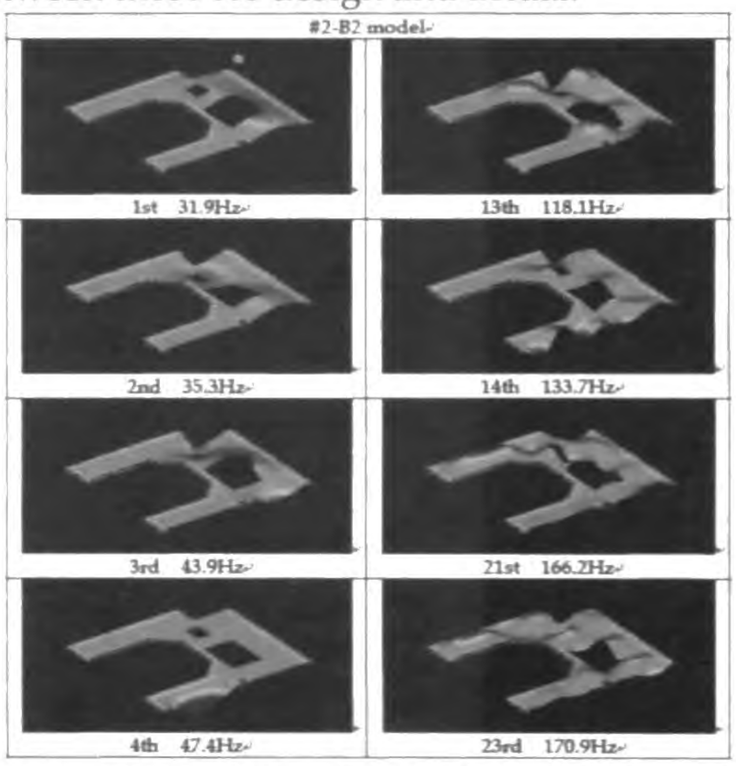
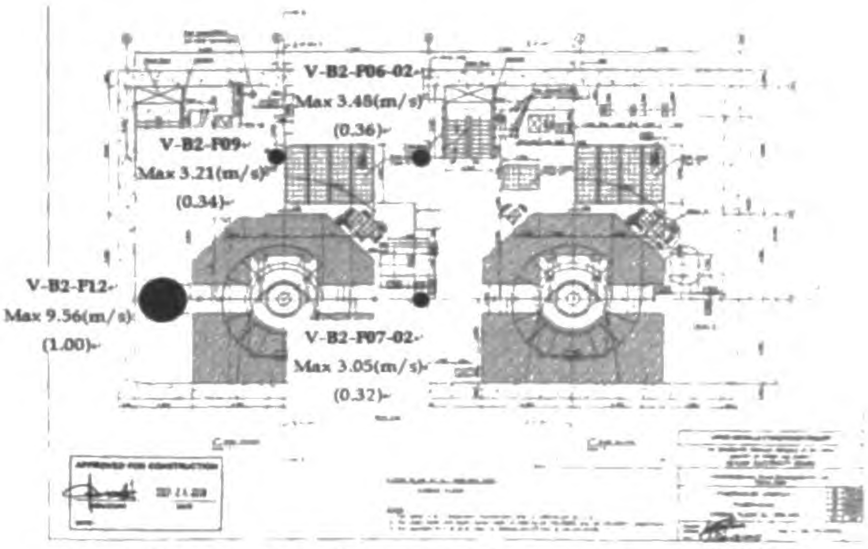


Figure 15 - Results of typical modal shapes in vertical component

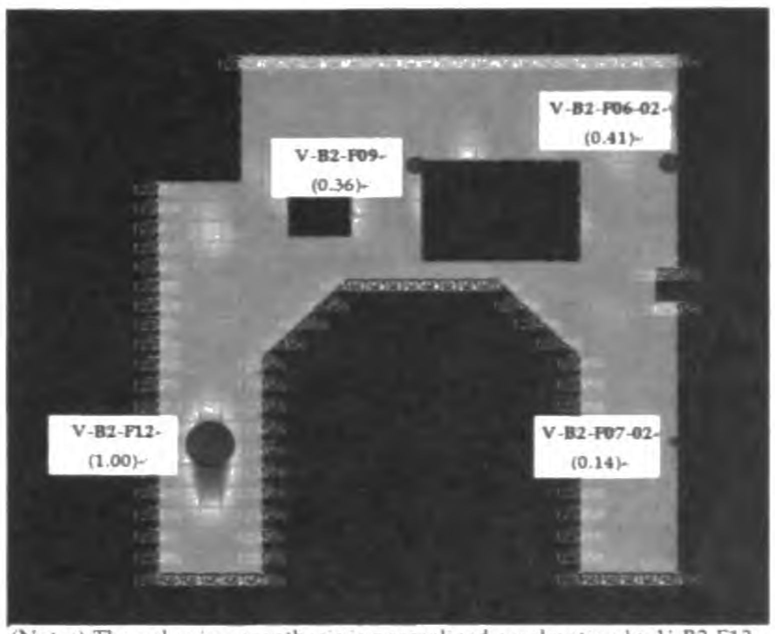
In order to compare the 23rd model shape between the measurement and the analysis, Fig.16 and Fig.17 indicate accelerations normalized by Measuring Point V-B2-F12.

From these figure, normalized accelerations only except for V-B2-F07-02 are almost the same between the measurement and the analysis. It seems that V-B2-F07-02 is affected by some local site effects. However, analytical results seem to be valid in general.
From these results, it is considered that the area around V-B2-F12 (the B2 floor in the side of Unit 2) is resonated and easily influenced by power plant operation.



(Notes) The value in parenthesis is normalized acceleration by V-B2-F12.

Figure 16 - Maximum acceleration from the measurement (B2 floor in the side of unit 2)



(Notes) The value in parenthesis is normalized acceleration by V-B2-F12.

Figure 17 - Maximum acceleration from the analysis (B2 floor in the side of unit 2)

5. Evaluation for Civil Structures

5.1 Penstock

Technical standard for gates and penstock (Electric Power Civil Eng. Acc., Japan) indicates that the criterion of judgment whether improvements against vibration are needed or not.
It is said that if half amplitude "d" does not exceed $D_0/2000$, improvement is not necessary (D_0: diameter of penstock).

・Criterion of half amplitude
$D_0/2000=1450(mm)/2000=0.7(mm)$ (5)

In the measurement, sinusoidal vibrations were recorded in 180Hz. Results of measurements show that maximum acceleration of the Penstock is about 50(m/sec^2) in 180Hz. From that, half amplitude of vibration can be roughly calculated.

・Half amplitude from measurement
$d=50(m/sec2)/(2*\pi*180)^2=0.04(mm)$ (6)

From the comparison of the results (5) and (6), improvement of the Penstocks is not needed for future stability of the Penstock.

5.2 Concrete Slab

Fatigue durability of concrete slab against the vibrations is assessed. The point V-B2-F12 which observed the largest acceleration on the floor is highlighted. In the evaluation, as a simplified calculation model, the floor is represented as shown in Fig.18.

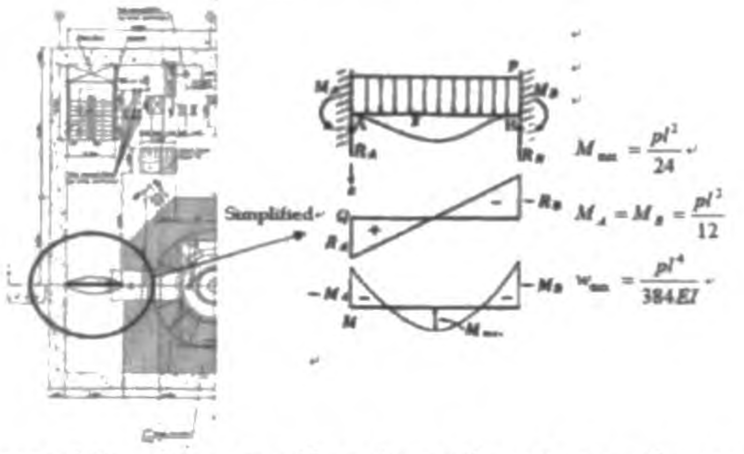


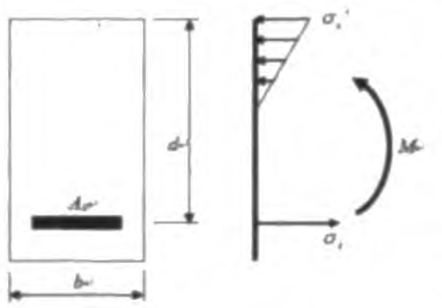
Figure 18 - Assumption to estimate maximum stress

At the point V-B2-F12, vertical maximum acceleration about 10(m/sec2) in 180Hz was observed. Vibration is assumed as monotonous sine wave, so vertical maximum displacement is estimated as follows.

Estimated vertical maximum displacement at V-B2-F12

w_v=10(m/sec^2)/(2*π*180)^2=0.008(mm)

Next, maximum stress of concrete and reinforcing bar caused by dead load (weight of concrete) and vibration is estimated. The stress is assessed as shown in Fig.19.



$$p = \frac{A_s}{bd}$$

$$j = 1 - \frac{k}{3}$$

$$k = -np + \sqrt{(np)^2 + 2np}$$

$$\sigma_c' = \frac{2M}{kjbd^2}$$

$$\sigma_s = \frac{M}{A_s jd}$$

where M : Bending moment
A_s : Area of cross section of reinforcing bar
n : Ratio of modulus of elasticity (Reinforcing bar / concrete)
σ_c' : Maximum compressive stress of concrete
σ_s : Maximum tensile stress of reinforcing bar

Figure 19 - Calculation of stresses of concrete and reinforcing bar

Estimated maximum stress caused by only dead load

Concrete : 0.52 (N/mm2)
Reinforcing bar : 18.9 (N/mm2)

Estimated maximum stress caused by only vibration

Concrete : 0.43 (N/mm2)
Reinforcing bar : 15.6 (N/mm2)

On the other hand, Standard Specifications for Concrete Structures -2007, Design (Japan Society of Civil Engineering) indicates procedure to evaluate fatigue strength as follows.

Fatigue strength of concrete

$$f_{rd} = k_{1f} \cdot f_d (1 - \sigma_p / f_d)\left(1 - \frac{\log N}{K}\right) \quad (7)$$

where f_{rd} : Fatigue strength of concrete
k_{1f} : 0.85 (in case of bending and compress)
f_d : Design strength of concrete
σ_p : Stress of concrete due to permanent load
K : 17 (in general)
N : Cycle number of the load

Fatigue strength of reinforcing bar

$$f_{srd} = 190 \frac{10^a}{N^k}\left(1 - \frac{\sigma_{sp}}{f_{ud}}\right) \Big/ \gamma_s \quad (8)$$

where f_{srd} : Fatigue strength of reinforcing bar
a : k_{0f}(0.81-0.003φ)
k_{0f} : 1.0 (in general)
φ : Diameter of reinforcing bar
k : 0.12 (in general)
N : Cycle number of the load
f_{ud} : Design tensile strength of reinforcing bar
σ_{sp} : Stress of reinforcing bar due to permanent load
γ_s : Material factor of reinforcing bar, 1.05 (in general)

Using this standard (Eq.(7) and (8)), The number of cycles to failure for concrete and reinforcing bar is estimated as follows.

Estimated number of cycles to failure
Concrete :1.3*10^{16}
Reinforcing bar :1.0*10^{12}

If the power plant will fully work for 24 hours, the cycle number of vibration due to power plant operation will be as follows.

Dominant frequency of vibration : 180 Hz
Maximum cycle number:
1.6*10^7 (times/1day)
5.7*10^9(times/1year)
5.7*10^{11}(times/100years)

From these results, the vibration of the floor will not give heavy damage to civil structures in powerhouse, because the cycle number of vibration will never exceed the maximum cycle number that may lead concrete slab to fatigue break within 100 years.

6. Conclusions

(1) Source of vibration is considered to be pulsatile water pressure caused by the runner vanes of the turbine.

(2) Evaluating the results of the measurements and analyses, improvements to avoid vibrations are not needed for the sake of civil structures. The vibration will not give heavy damage to civil structures in powerhouse.