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# DYNAMIC STABILIZATION OF FOLSOM DAM TAINTER-GATES BY REPLACING HOIST CHAINS WITH CABLES

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**Abstract.** *As dam crest gates, Tainter-gates (radial gates) are used for regulation and flood release. While Tainter-gate failures are infrequent, many Tainter-gates are susceptible to self-excited vibration at small gate openings and cannot be operated at these small openings. However, one notable failure did occur on 17 July l995. One of the 87-ton Tainter-gates at the Folsom Dam in California failed, likely due to flow-induced vibrations. To prevent a recurrence of such Tainter-gate failures, the authors have pursued an extensive research programs. These studies lead to the conclusion that the underlying mechanism behind the Folsom Dam failure was an essential dynamic instability mechanism that all Tainter-gates may inherently possess. The failed Folsom Tainter-gate has been shown to possess an intense dynamic instability according to theoretical calculations. This paper explores a method of extending the region dynamic stability for this gate. After an initial review of the method of calculation of the dynamic stability of gates, the stabilization method is presented. Stability can be attained through the design of a new hoist cable for the gate to replace the present hoisting system. The effectiveness of this retrofit was confirmed in model experiments. Subsequently, design dimensions of the hoist cable needed to extend the range of dynamic stability for the full-scale Folsom Tainter-gate was calculated. The method presented in this paper can be readily applied to assure long-term stable operation of Tainter-gates. It requires no major modifications to or replacement of the gate structure.*

## 1 INTRODUCTION

Tainter-gates (also known as radial gates) are frequently used for water-level regulation in impoundment dams. As shown in Figure 1, the Tainter-gate has a circular-arc skinplate, centered on the trunnion pin. Therefore, the loading due to hydraulic pressure on the skinplate is concentrated on the trunnion pin. Further, the gate opening is controlled by winding or unwinding support chains or cables, which are attached to the skinplate at a significant distance from the trunnion pin. As a result, the force required to open the gate is significantly smaller than that required to open a sluice gate with an equivalent scale. For this reason, the Tainter-gate design is advantageous for large-scale installations.

The Tainter-gates installed in the Folsom Dam in California have circular-arc skinplates with a height of 15.5 m and a radius of 14.33 m, as shown in Figure 1. The spanwise length is 12.8 m and the whole gate mass is 87 tons. During operation on July 17, 1995, one of the Folsom Dam gates failed [1~4]. Vibration tests of a remaining gate [1, 5] and of a reinforced gate undertaken as part of the failure investigation, identified the two significant natural vibration modes illustrated in Figure 1. One mode was the rigid-body rotational lifting vibration of the whole gate about the trunnion pin, as denoted by $\Theta$ in Figure 1. The second significant mode was a relatively low frequency streamwise bending of the skinplate (see the dotted lines), as denoted by $\Psi$ in Figure 1. The motion of one vibration mode enhances the displacement in the other mode and vice versa. This type of coupled-mode vibration is accompanied by a variation in the gate's discharge (a flow rate variation), thus potentially inducing an intense self-excited vibration [6, 7]. This mechanism may have caused, or contributed to, the Folsom Dam gate failure, as well as gate incidents at other dams.

The existence of coupled-mode, self-excited vibration in Tainter-gates has been confirmed in tests of 2-D and 3-D model gates [7~9], and it has been theoretically predicted that operational, full-scale Tainter-gates could potentially undergo coupled-mode, self-excited vibration [7, 10~12].

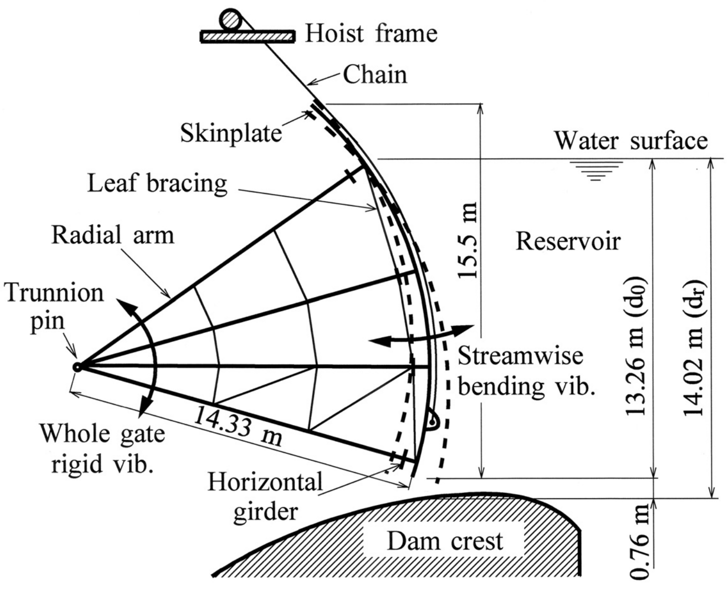



Figure 1: Side view of an 87-ton Tainter-gate from the Folsom Dam in California, showing two predominant natural vibration modes.

The greatest concern stemming from our studies is that a significant number of operational Tainter-gates may be susceptible to this intense dynamic instability. Therefore, retrofit countermeasures must be developed. Any Tainter-gate found to be dynamically unstable should be retrofitted with a countermeasure to prevent a failure similar to that of the Tainter-gate at the Folsom Dam. Establishment of an additional design criterion that assures the dynamic stability of Tainter-gates in new gate installations is also needed.

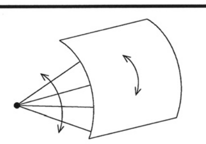
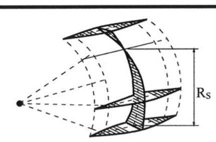
One basic concept for the long-term stable operation of a Tainter-gate, presented in this paper, is to reduce the whole gate rigid body vibration frequency to a value that eliminates the coupling of the two vibration modes. As an example of the implementation of this concept, wire cables are designed to replace the hoist chains in the reinforced Folsom Tainter-gate to maintain dynamic stability.

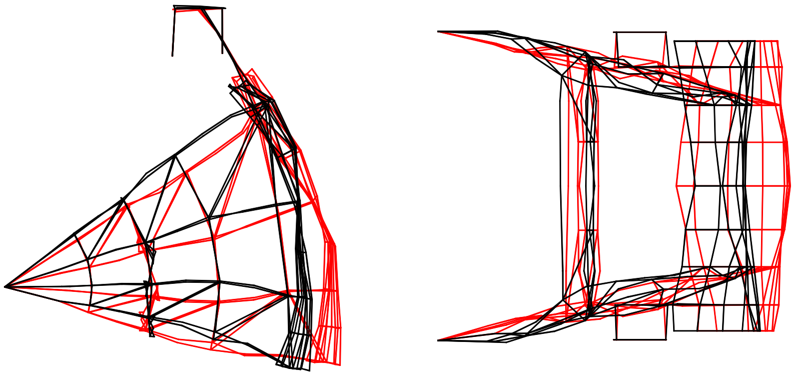
## 2 DYNAMIC INSTABILITY OF THE REINFORCED FOLSOM GATE

After the 1995 gate failure, the remaining Folsom Tainter-gates were reinforced. Additional plates were welded onto the radial arms, additional diagonal members were attached between radial arms, additional diagonal braces were attached between cross beams, additional girder bracings were added, and all joints were welded. No changes were made to the skinplate. To confirm the effect of reinforcement from the structural dynamics viewpoint, additional experimental modal analyses were conducted on the reinforced gate [7, 13].

The in-air natural vibration characteristics resulting from the modal analysis of the reinforced Folsom gate are shown in Table 1. Also included Table 1, for comparison, are the corresponding results from similar testing on the original gate. The fundamental mode $N_{x2}$, is for a streamwise bending vibration of the skinplate. As shown in Figure 2(a), the skinplate vibrated in a bending mode, similar to the mode $M_{x21}$ for the original gate. The nodal line is located near the top of the skinplate. As shown in Figure 2(b), the skinplate exhibited a half wavelength spanwise mode shape, with nodes at the spanwise ends. The natural vibration frequency $\Omega_{na\psi}$ of this mode was 27.9 Hz, and the damping ratio $\zeta_{na\psi}$ was 0.004. Both the natural vibration frequency and damping ratio are slightly larger, relative to the original gate. This increase is due to the increased bending rigidity of the skinplate resulting from the reinforcement of the radial arm structures. On the other hand, the whole gate performs rigid body rotational vibration around the trunnion pin, with a vibration frequency of $\Omega_{na\theta}$ = 6.75 Hz and a damping ratio of $\zeta_{na\theta}$ = 0.009. Reinforcement increased the gate mass, reducing the natural vibration frequency of whole gate vibration after reinforcement. The damping ratios are quite small, even after reinforcement for both the whole gate rotational vibration around the trunnion pin and for the skinplate streamwise bending vibration.

Table 1: Effect of reinforcement on the modal vibration frequencies and on modal damping.

| Original Gate | | | Vibration Mode Shape | Reinforced Gate | | |
|---|---|---|---|---|---|---|
| Mode Name | Frequency (Hz) | Damping Ratio | | Mode Name | Frequency (Hz) | Damping Ratio |
| $M_{z21}$ | 6.88 | 0.012 |  | $N_{xz21}$ | 6.75 | 0.009 |
| $M_{x21}$ | 26.9 | 0.002 |  | $N_{x2}$ | 27.9 | 0.004 |



(a) Side view (b) Downward view

Figure 2: Fundamental mode shape for the skinplate streamwise bending vibration of the reinforced Folsom Dam Tainter-gate for Mode $N_{x2}$ ($\Omega_{na\psi}$= 27.9 Hz; $\zeta_{na\psi}$= 0.004).

These test results show that, despite reinforcement, the frequencies for the whole gate rotational vibration around the trunnion pin and the circular-arc skinplate streamwise bending vibration have changed only slightly from those for the original gate. It is suspected, based on the earlier analysis of the original gate, that these two modes can still couple with each other to produce coupled-mode self-excited vibration. Analysis of the reinforced gate confirms this suspicion.

In the theoretical analysis for the coupled-mode self-excited vibration of Tainter-gates, developed by Anami & Ishii [6,14] and Anami [7], the skinplate rotational streamwise bending vibration is assumed to be represented by an equivalent rigid body rotational vibration with very small amplitude. The whole gate rotation around the trunnion pin induces a flow rate variation beneath the gate, with a corresponding "flow-rate variation pressure" which forces the skinplate to vibrate in the streamwise direction. Subsequently, the skinplate streamwise vibration induces a "push-and-draw pressure," manifested as an added mass that significantly lowers the vibration frequency of the skinplate. Since the gate discharge is not submerged, vortex phenomena play no role; hence, these hydrodynamic pressures can be theoretically calculated by a potential theory developed by Rayleigh [15] for dissipative wave-radiation problems. With theoretically derived expressions for the hydrodynamic pressures, the coupled-mode self-excited vibration of Tainter-gates can be analyzed theoretically [16,17]. The mechanism of the coupling of streamwise and whole gate vibrations through the hydrodynamic and inertial forces was first identified by Anami & Ishii [7, 14].

The equations of motion of this coupled-mode vibration can be reduced to the following non-dimensional expressions:

$$\theta'' + 2\zeta_{a\theta}\theta' + \theta = -\frac{\alpha_I}{\alpha_*}\psi'' \tag{1}$$

and

$$\begin{aligned}&\left(1 + \delta_p\alpha_\psi\Delta m_\psi^* + \sqrt{2}\,c_f k\delta_p\alpha_\psi\Delta m_\theta^*\right)\psi'' \\ &+ 2\gamma_{\psi\theta}\left(\zeta_{a\psi} + \frac{\delta_p\alpha_\psi\Delta c_\psi^*}{2\gamma_{\psi\theta}F_{0\theta}} - \sqrt{2}\,c_f k\frac{\delta_p\alpha_\psi\Delta c_\theta^*}{2\gamma_{\psi\theta}F_{0\theta}}\right)\psi' + \gamma_{\psi\theta}^2\psi \\ &= \alpha_*\left\{-\left(\alpha_{I\psi} + \sqrt{2}\,c_f\frac{\delta_p\alpha_\psi\Delta m_\theta^*}{r_{sa}}\right)\theta'' + \sqrt{2}\,c_f\frac{\delta_p\alpha_\psi\Delta c_\theta^*}{r_{sa}F_{0\theta}}\theta'\right\}.\end{aligned} \tag{2}$$

The neutrally stable dynamic stability curve (the dynamic stability criterion) in the stability diagram was calculated from the solutions to the equations of motion. The calculated dynamic stability diagrams for the reinforced and original Folsom Tainter-gates for the operating conditions (upsteam reservoir level and gate opening) present at the time of the 1995 failure are shown in Figure 3. The solid line is for the reinforced gate while the dashed line is for the original gate. The ordinate represents the fluid excitation ratio, which in other words, is the damping ratio needed to maintain dynamic stability, called the "stability damping ratio." The abscissa is the frequency ratio $\gamma_{nw}$ ($= \Omega_{nw\psi}/\Omega_{a\theta}$) of the in-water streamwise natural vibration of the skinplate to that of the in-air whole gate rotational vibration around the trunnion pin. Of great significance is that the unstable region for the reinforced gate is larger than that for the original gate.

The in-air skinplate streamwise natural vibration frequency $\Omega_{na\psi}$ of 27.9 Hz was drastically reduced due to the water added mass effect. If the lowered in-water natural vibration frequency approaches more closely the natural vibration frequency of whole gate vibration around the trunnion pin, the frequencies of the two modes of vibration coalesce. The theoretical analysis indicates that the in-air natural vibration frequency $\Omega_{na\psi}$ of 27.9 Hz is reduced to 6.42 Hz in water ($\Omega_{nw\psi}$). The proximity of this value of 6.42 Hz to the in-air natural vibration frequency $\Omega_{na\theta}$ of 6.75 Hz for the whole gate vibration around the trunnion pin is of great significance. Note also that the frequency of $\Omega_{nw\psi}$= 6.42 Hz is slightly smaller than the frequency of $\Omega_{a\theta}$= 6.75 Hz, resulting in a vibration frequency ratio of $\gamma_{nw}$ ($= \Omega_{nw\psi}/\Omega_{a\theta}$) = 0.95. The single data point plotted in Figure 3 corresponds to this frequency ratio of $\gamma_{nw}$ = 0.95 and the damping ratio for the skinplate streamwise vibration of $\zeta_{a\psi}$ = 0.004. The plotted condition point is in the region of intense dynamic instability.

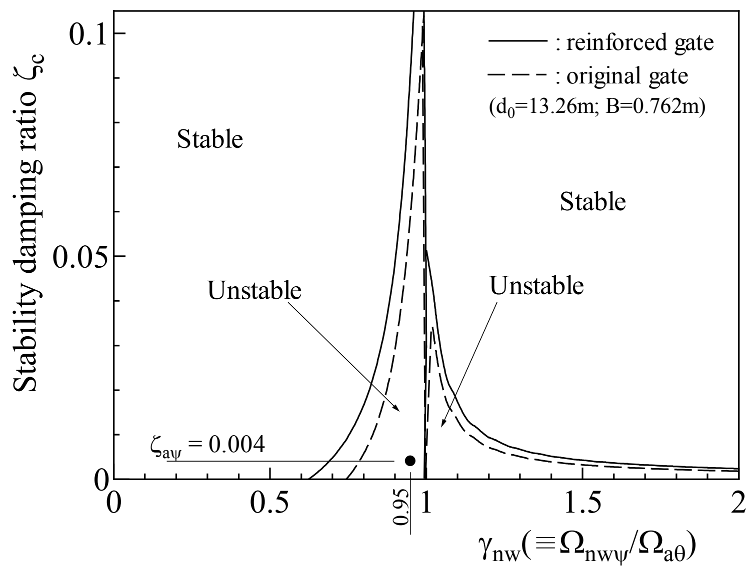



Figure 3: Dynamic stability diagram for the Folsom Dam reinforced gate, compared with that for the original gate at the water level and gate opening prevailing in the 1995 failure ($d_0$ = 13.26 m, $B$ = 0.76 m).

## 3 SPRING CONSTANT FOR DYNAMIC STABILITY OF REINFORCED FOLSOM GATE

In order to maintain dynamic stability for the reinforced Folsom gate, the condition point of the gate (plotted in Figure 3) must be forced into one of the stable regions. Since the condition point is known to move to the right with increasing upstream reservoir depths, the condition point must be forced into the stable region on the right side of Figure 3 ($\gamma_{nw} > 1.0$) to assure complete dynamic stability for all reservoir depths.

In the unstable region for $\gamma_{nw} > 1.0$, the coupled-mode vibration is synchronized with the whole gate vibration. Therefore, the damping ratio for whole gate vibration will be used to determine conditions for the dynamic stability. The critical frequency ratio $\gamma_{nw}$ for stability is about 1.20 with the whole gate damping ratio of 0.009. Thus, for a frequency ratio $\gamma_{nw} > 1.27$, the condition point will be stable with at least a 5% safety margin, as shown in Figure 4.

Knowing the frequency ratio and the in-water bending mode frequency, the spring constant required to maintain stability can be calculated. The radius of the Folsom Tainter-gate, $R_a$ is 14.33 m. The moment of inertia of the whole gate around the trunnion pin, $I_\theta$ is $1.31\times10^7$ $\text{kg}\cdot\text{m}^2$. The whole gate rotational vibration frequency is given by the following expression:

$$\Omega_{a\theta}\left[Hz\right] = \frac{1}{2\pi}\sqrt{\frac{K_e R_a^2}{I_\theta}}\,. \tag{3}$$

Therefore, the required spring constant is as follows:

$$K_e = \frac{\Omega_{a\theta}^2 4\pi^2 I_\theta}{R_a^2} = 64.35\times10^6\ \text{N/m}. \tag{4}$$

When the spring constant of the gate lifting wire cable, $K_e$ is smaller than $64.35\times10^6$ N/m, the whole gate vibration frequency $\Omega_{a\theta}$ is less than or equal to 5.06 Hz, and the gate possesses complete dynamic stability under any conditions.

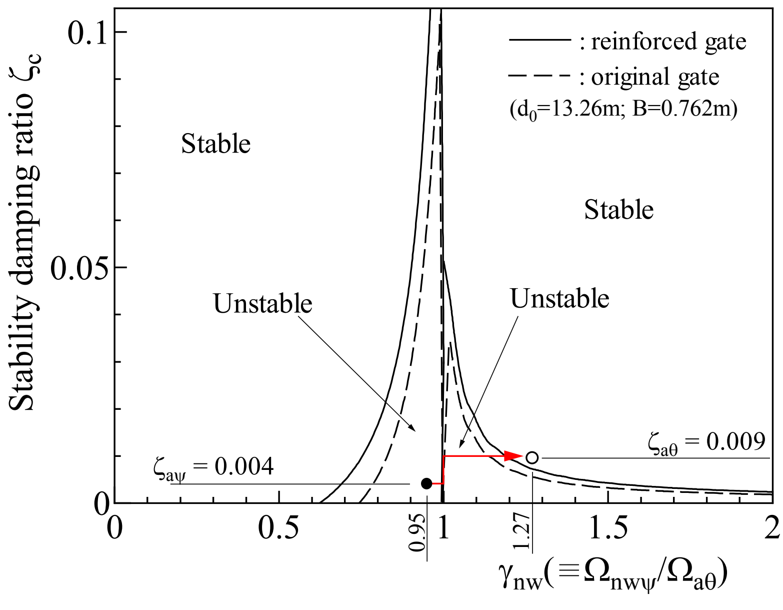



Figure 4: Vibration frequency ratio $\gamma_{nw}$ needed for complete dynamic stability (unfilled data point).

## 4 DESIGN OF GATE LIFTING WIRE CABLES FOR COMPLETE DYNAMIC STABILITY OF REINFORCED FOLSOM GATE

The lifting load should include the whole gate mass $M$ and hydraulic load due to friction at the trunnion pin $F_t$ and the skinplate side seals $F_s$. Assuming a 20% safety margin, the lifting load $Q$ can be estimated as follows:

$$Q = 1.2 \times (M + F_t + F_s) = 1{,}128 \times 10^3 \Rightarrow 1{,}130 \times 10^3 \quad \text{(N)} \tag{5}$$

When the safety factor $S$ is set to 6, the required capacity of each wire cable, $T$ is as follows:

$$T = \frac{1}{n} QS \tag{6}$$

where, $n$ represents the combined total number of wire cables on the two sides of the gate.

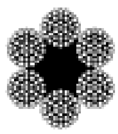
When the gate is raised with two wire cables on each side of the gate (a combined total of four cables), the breaking load per wire is about 1,700 kN. The wire cable characteristics to carry this load are given in Table 2, assuming each cable is a 6×37 wire cable commonly used in Japan for gates.

The length of wire cables for the Folsom gate, $L$, is 16.418 m. It follows that the spring constant for the wire cables can be given as:

$$K_e = n\frac{AE}{L} = 32.35 \times 10^6 \quad \text{(N/m)} \tag{7}$$

This value is substantially smaller than the value $64.35 \times 10^6$ (N/m) needed for dynamic stability. Using the spring constant in Equation 7, the in-air whole gate vibration frequency calculated using Equation (3) is 3.58 Hz. The corresponding in-water natural vibration frequency ratio $\gamma_{nw}$ of 1.79 is substantially larger than 1.27, assuring the complete dynamic stability of the gate.

Table 2: Wire cable characteristics.

| | | | | |
|---|---|---|---|---|
|  | name | 6×37 | | |
| | construction | 6×(1+6+12+18) | | |
| | Type | G, galvanized, pre-tensioned | | |
| | | | | |
| diameter of wire cable $d_w$ (mm) | diameter of strand $\delta$ (mm) | area A ($mm^2$) | breaking load T (kN) | modulus of elasticity E (MPa) |
| 60 | 2.86 | 1140 | 1780 | 92,200 |

When the hoist chains are replaced by wire cables, the portions of the wire cable in contact with the skinplate may exhibit almost no elongation. As a worst case, assume only the free length of the wire cables act as a spring. For Folsom gate, the free length of wire cable $L'$ is 7.35 (= 16.418 - 9.07) m from the blueprint of the gate. In this worst case scenario, the spring constant of the wire cables is as follows:

$$K_e = n\frac{AE}{L'} = 57.22 \times 10^6 \quad \text{N/m} \tag{8}$$

This value of spring constant is still less than the value of $64.35 \times 10^6$ N/m needed for dynamic stability. The corresponding value of the in-air whole gate vibration frequency is 4.77 Hz and the in-water natural vibration frequency ratio $\gamma_{nw}$ is 1.35, which is larger than 1.27, the value needed for complete dynamic stability.

## 5 CONCLUSIONS

Based on the dynamic characteristics of the gate obtained via modal analysis, a simple and easily implemented retrofit was proposed to assure the complete dynamic stability of the reinforced Folsom gates. Using the vibration frequency ratio needed for dynamic stability as a guide, specifications were developed for hoist wire cables to replace the currently used hoist chains. Replacing the current hoist chains with two wire cables on each side of the skinplate would assure the complete dynamic stability of the reinforced Folsom gate.

It is the authors' firm belief, documented through their sustained research program over the past 18 years, that coupled-mode dynamic instability contributed to the failure of the Folsom Dam gate. The awareness of the dynamic instability mechanism and its highly likely (almost certain) role must be transmitted to subsequent generations of hydraulic structures engineers all over the world. Operational Tainter-gates susceptible to this dangerous intense dynamic instability should be identified, as soon as possible. The present study can provide a framework and the basic concepts needed to create design guidelines for the design of dynamically stable Tainter-gates.

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