THE GOVERNING EQUATIONS FOR SURGING AT THE SURGE CHAMBER OF THE TAIL-RACE TUNNEL DUE TO LOAD REJECTION*

放水路サージ チャンバーにおける 負荷遮断時のサージング計算式

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SYNOPSIS

In course of down surging at the surge chamber of the initially full-flowing tail-race tunnel, the entrance of the free surface into the tunnel makes it impossible for the conventional surging equations for the pressure conduit to govern the surging at the surge chamber of the tail-race tunnel. New governing equations for this case are developed for practical design purposes by modifying the conventional surging equations for the pressure conduit. Special emphasis is laid to the maximum rise of the water level in the surge chamber in consequence of the counter flow in the tunnel subsequent to the down surging at load rejection, since the maximum rise is an inevitable top surge. Surging waves are worked at by arithmetical integration of the new equations and are compared with those given by experiment. A satisfactory agreement is shown at the comparison, through which validity of the new governing equations is affirmed.

INTRODUCTION

When the load is rejected suddenly from a hydro-electric station with a full-flowing tail-race tunnel at the top of which a surge chamber is provided, the inertia of the water flowing in the tail-race tunnel lowers the water level in the surge chamber, in general, until the free surface penetrates into the upper part of the tunnel (see **Photo. 1**). Once the minimum ordinate is attained, the water level in the surge chamber rises, eventually, up to beyond the initially working water level. This maximum rise calls attention, since the sudden load rejection is inevitable. The maximum rise should therefore be considered as an inevitable top surge, which might be more important than that which is due to the load increase the rate of which is controlled artificially. In order to calculate the surging behavior after load-rejection, new governing equations are required, since the admission of the free surface in the tail-race tunnel makes the conventional surging equations for the pressure tunnel impossible to govern the surging at the surge chamber of the tail-race tunnel.

The purpose of this investigation is to develop the new governing equations by modifying the conventional surging equations for the pressure tunnel and to check them experimentally.*** Although theoretical investigation is presented in advance of experiment in this paper, the former is the result derived from the latter conducted since 1952.

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* Read at the Annual Meetings of the Japan Society of Civil Engineers, 1954 and 1955.

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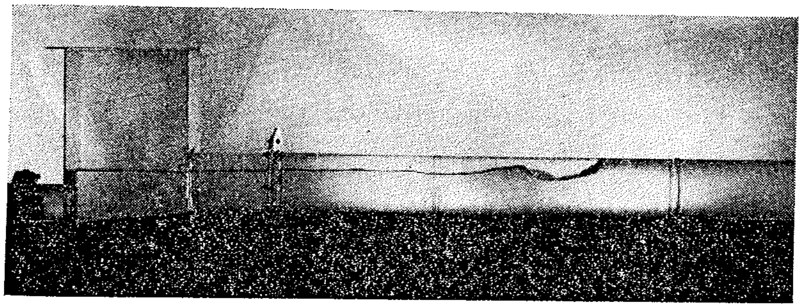
*** The general problem of the surging at the tail-race tunnel due to load increase has been treated by Prof. Meyer-Peter and Dr. Favre [Ref. 1,2]. In the case of load rejection at the full-flowing tail-race tunnel without a surge chamber, Prof. Escande and Dr. Nougaro [Ref. 3] have made an extensive study. Experimental study of the surging at the tail-race tunnel due to both load increase and load rejection has recently been published by Dr. Blind [Ref. 4].

THEORY

When the water surface lowers due to the load rejection below the top of the tail-race tunnel inlet and air is admitted into the tunnel, the mechanism immediately responsible for the actual change in water surface elevation is a procession of translatory negative waves traversing the length of the tunnel against a negative hydraulic gradient. (cf. **Photo. 1**).

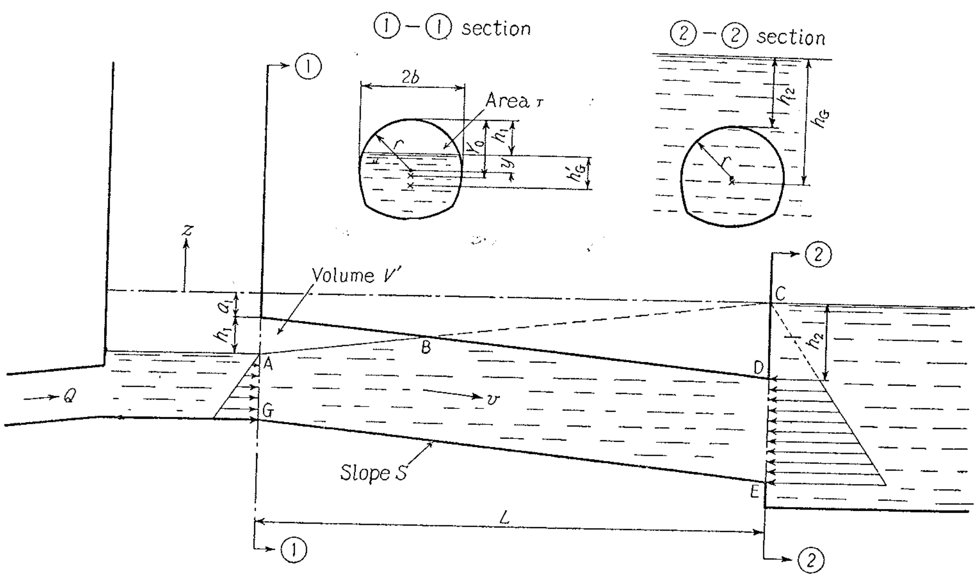
Photo. 1 A translatory negative wave progressing into the tail-race tunnel due to an instatenous rejection of load.



However, in order to make an approximate representation of the wave problem with the oscillation equations similar to the conventional surging equations, assumptions will be taken by referring to **Fig. 1** as follows:

1. Hydraulic gradient is represented by the straight line connecting point C, the point at the water surface at the exit of the tunnel, and point B, the front of the negative wave.
2. Point B, the front of the negative wave, is on the straight line connecting point C and point A, the point at the water surface at the entrance of the tunnel.
3. The inertia of flowing water which contributes to the equation of motion is that which is due to the mass of water of the portion ABDEGA.

Fig. 1 Assumed shape of water surface and hydraulic gradient during the surging at load rejection.



The resulting simplified differential equation of motion for load rejection is

$$\frac{W}{g}\frac{dv}{dt}=P_1-P_2+WS\mp Kv^2, \qquad (1)$$

where

W: mass of water of the portion ABDEGA,

P_1: resultant of hydrostatic pressure acting at the entrance of the tunnel upon the flowing water in the tunnel,

P_2: resultant of hydrostatic pressure acting at the exit of the tunnel upon the flowing water in the tunnel,

S: slope of the longitudinal axis of the tunnel,

v: mean velocity of water at full-flowing part of the tunnel,

t: time,

g: acceleration of gravity,

K: a coefficient such that Kv^2=total frictional resistance in the tunnel.

In order to transform the above equation to the form similar to the conventional equation of motion at the pressure conduit with a surge tank*, let us take up the following relations by referring to **Fig. 1**.

$$W=w(fL-V'), \qquad (2.a)$$

$$P_1=w(f-f')h_G', \qquad (2.b)$$

and

$$P_2=wfh_G, \qquad (2.c)$$

where

w: weight of water per unit volume,

f: cross sectional area of the tail-race tunnel,

L: length of the tunnel,

V': total volume of the upper space above the free surface in the tunnel,

f': cross sectional area of the upper space above the free surface at the section of the inlet of the tunnel,

h_G': depth of the center of gravity of the area below the free surface at the section of the inlet of the tunnel,

h_G: depth of the center of gravity of the cross sectional area of the tunnel at the section of the exit of the tunnel.

Substituting the relations (2) into eq. (1) and dividing through by wf, we obtain

$$\frac{L-\frac{V'}{f}}{g}\frac{dv}{dt}=\left(1-\frac{f'}{f}\right)h_G'-h_G+\left(L-\frac{V'}{f}\right)S\mp cv^2, \qquad (3)$$

where

c: a coefficient such that cv^2=total losses of head at full flowing flow in the tunnel.**

The above equation is the form more similar to the conventional equation of motion than equation (1) is. Yet the presence of the unusually measurable length h_G' in the equation is still annoying. In order to express h_G' by more usual quantities, let us make use of a few

* As the conventional equation of motion at the pressure conduit with a surge tank is here meant the equation

$$\frac{dv}{dt}=\frac{z\mp cv^2}{L/g},$$

which will appear later in its place in eqs. (13).

** As is obvious, c is related with K in eq. (1) as $c=K/(wf)$.

geometrical relations. The sum of the moments of area f' and area $f-f'$, around the axis $O'O'$ (**Fig.** 2), being the moment of the total area f around the same axis,

$$f'Y_1+(f-f')Y_2=fY_0,$$

where,

Y_0, Y_1, Y_2: vertical distances as shown in **Fig.** 2.

Hence

$$Y_2=\frac{fY_0-f'Y_1}{f-f'}.$$

Combining the above equation and the relation $h_G'=Y_2-h_1$, we obtain the relation between h_G' and Y_0-h_1 as

$$\left(1-\frac{f'}{f}\right)h_G'=Y_0-h_1+\frac{f'}{f}(h_1-Y_1) \quad \cdots\cdots(4)$$

On the other hand, by referring to **Fig.** 3 and **Fig.** 2 we note the relations

$$Y_0-h_1+LS-h_G=z$$

and

$$h_1-Y_1=y_1-y,$$

respectively, where

z: water level in the surge chamber,

y and y_1: distances as shown in **Fig.** 2.

Fig. 2 Nessesary notations related with centers of figure. (G_0, G_1 and G_2 are centers of figure of area f, f' and f-f', respectively.)

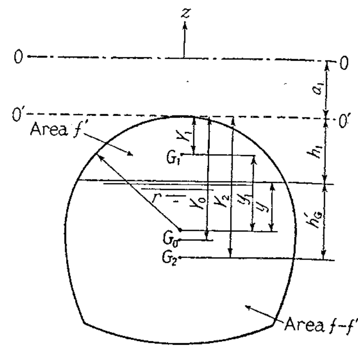
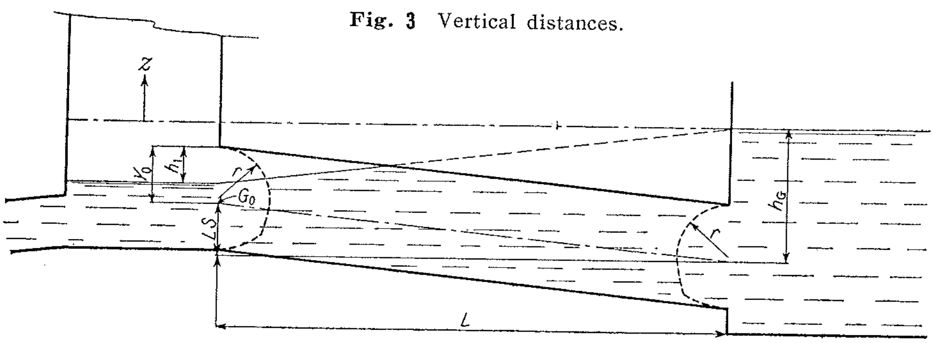


Fig. 3 Vertical distances.



Substituting eq. (4) to eq. (3) and making use of the above two relations, we obtain

$$\frac{L-\dfrac{V'}{f}}{g}\,\frac{dv}{dt}=z+\frac{f'}{f}(y_1-y)-\frac{V'}{f}S\mp cv^2 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(5)$$

h_G' has thus been eliminated out of eq. (3). The above equation, however, contains the quantity y_1, which shall also be expressed by other more usually measurable quantities. With reference to **Fig.** 4, according to formulae of geometry [Ref. 5], y_1 and f' are given by

$$y_1=\frac{2}{3}\,\frac{b^3}{f'}, \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(6.\mathrm{a})$$

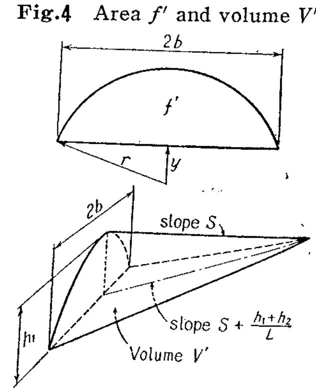
and

$$f'=r^2\left[\sin^{-1}\frac{b}{r}-\frac{y}{r}\,\frac{b}{r}\right], \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(6.\mathrm{b})$$

and V', by the use of an assumption $S \ll (h_1+h_2)/L$, by

$$V'=\frac{L}{h_1+h_2}r^3\left[\frac{2}{3}\left(\frac{b}{r}\right)^3-\frac{y}{r^3}f'\right] \quad \cdots\cdots\cdots\cdots\cdots(6.\mathrm{c})$$

Fig.4 Area f' and volume V'.



Therefore,

$$\frac{f'}{f}(y_1-y)=\frac{f'}{f}\left(\frac{2}{3}\frac{b^3}{f'}-y\right)=\frac{1}{f}\left(\frac{2}{3}b^3-f'y\right)=\frac{h_1+h_2}{L}\frac{V'}{f}\,.$$

Substituting the above relation in eq. (5) and noting

$$\frac{h_1+h_2}{L}-S=\frac{1}{L}(h_1+h_2-LS)=-\frac{z}{L},$$

we obtain

$$\frac{L-\dfrac{V'}{f}}{g}\frac{dv}{dt}=\left(1-\frac{V'}{Lf}\right)z\mp cv^2\,.$$

Dividing through by $[L-(V'/f)]/g$, we obtain

$$\frac{dv}{dt}=\frac{z\mp\left[cv^2\Big/\left(1-\dfrac{V'}{Lf}\right)\right]}{L/g}, \qquad \text{(7)}$$

which is the required form of equation of motion.

With the equation of motion thus established, it is necessary to establish the equation of continuity. From consideration of hydraulic continuity,

$$F\,\Delta z+\Delta V'=(Q-fv)\Delta t \qquad \text{(8.a)}$$

Hence,

$$F\frac{dz}{dt}+\frac{dV'}{dt}=Q-fv, \qquad \text{(8.b)}$$

where

F: area of water surface in the surge chamber,

Q: turbine discharge,

$\Delta z, \Delta V'$: increment of z and V' during infinitesimal time period Δt, respectively.

Since

$$\frac{dV'}{dt}=\frac{dV'}{dz}\frac{dz}{dt}=-\frac{dV'}{dh_1}\frac{dz}{dt}\,^*,$$

(8.b) is rewritten as

$$\left(F-\frac{dV'}{dh_1}\right)\frac{dz}{dt}=Q-fv \qquad \text{(8.c)}$$

In order to express dV'/dh_1 in the above equation more explicitly, let us put (6.c) in dV'/dh. Then,

$$\frac{dV'}{dh_1}=Lr^3\left[\frac{-1}{(h_1+h_2)^2}\left\{\frac{2}{3}\left(\frac{b}{r}\right)^3-\frac{y}{r}\frac{f'}{r^2}\right\}+\frac{1}{h_1+h_2}\left\{2\frac{b^2}{r^3}\frac{db}{dh_1}-\frac{1}{r^3}\left(\frac{dy}{dh_1}f'+y\frac{df'}{dh_1}\right)\right\}\right]. \qquad \text{(9.a)}$$

Making use of the relations

$$\frac{db}{dh_1}=\frac{y}{b},$$

$$\frac{df'}{dh_1}=2b,$$

and

$$\frac{dy}{dh_1}=-1,$$

* The positive direction of h_1 is taken vertically downward. The length of h_1 is as shown in the previous figures.

we obtain from equation (9.a)

$$\frac{dV'}{dh_1}=Lr^3\left[\frac{-1}{(h_1+h_2)^2}\left\{\frac{2}{3}\left(\frac{b}{r}\right)^3-\frac{y}{r}\frac{f'}{r^2}\right\}+\frac{1}{h_1+h_2}\frac{f'}{r^3}\right]$$
$$=\frac{Lr^3}{h_1+h_2}\left[\frac{-1}{h_1+h_2}\left\{\frac{2}{3}\left(\frac{b}{r}\right)^3-\frac{y}{r}\frac{f'}{r^2}\right\}+\frac{f'}{r^3}\right]\cdots\cdots(9.\mathrm{b})$$

Substituting (6.c) in the last member of the above equation, we obtain

$$\frac{dV'}{dh_1}=\frac{1}{h_1+h_2}[-V'+Lf']\cdots\cdots(9.\mathrm{c})$$

From equations (8.c) and (9.c) we obtain

$$\left[F+\frac{L}{h_1+h_2}\left(f'-\frac{V'}{L}\right)\right]\frac{dz}{dt}=Q-fv,$$

and, thus,

$$\frac{dz}{dt}=\frac{Q-fv}{F+\dfrac{L}{h_1+h_2}\left(f'-\dfrac{V'}{L}\right)},\cdots\cdots(10)$$

which is the required form of equation of continuity. $\frac{L}{h_1+h_2}f'$ which appears in the denominator of the right member of the above equation represents the area of the free surface AB in **Fig. 1**. Therefore, what is represented by the denominator of the right member of the above equation is understood to be the area of the total free surface of water to which a slight modification is made, through the term V'/L, due to the rotation of the free surface AB around the point C.

For convenient reference, fundamental equations derived are summarized as follows:

$$\left.\begin{aligned}
&\frac{dv}{dt}=\frac{z\mp\left[cv^2\Big/\left(1-\dfrac{V'}{Lf}\right)\right]}{L/g},\\
&\frac{dz}{dt}=\frac{Q-fv}{F+\dfrac{L}{h_1+h_2}\left(f'-\dfrac{V'}{L}\right)},\\
&f'=r^2\left[\sin^{-1}\frac{b}{r}-\frac{y}{r}\frac{b}{r}\right],\\
&V'=\frac{L}{h_1+h_2}r^3\left[\frac{2}{3}\left(\frac{b}{r}\right)^3-\frac{y}{r^3}f'\right].
\end{aligned}\right\}\cdots\cdots(11)$$

The values of the non-dimensional functions

$$\left.\begin{aligned}
&\frac{f'}{r^2}=\sin^{-1}\frac{b}{r}-\frac{y}{r}\frac{b}{r}\equiv\varphi,\\
\text{and}\quad&\frac{V'}{Lr^3/(h_1+h_2)}=\frac{2}{3}\left(\frac{b}{r}\right)^3-\frac{y}{r^3}f'\equiv\psi
\end{aligned}\right\}\cdots\cdots(12)$$

are given in **Fig. 5**.

By any proper method of integration* of eqs. (11) surging behaviour at the surge chamber of the tail-race tunnel will be analysed.

For the special instance the location of the tail-race tunnel is deep enough to prevent air from entering the tunnel even when the down surge is a maximum, f' and V' are always zero and the eqs. (11) are reduced to

* An example of arthmetical integration of eqs. (11) is shown in the appendix at the end of this paper.

Fig. 5 Values of φ and ψ.

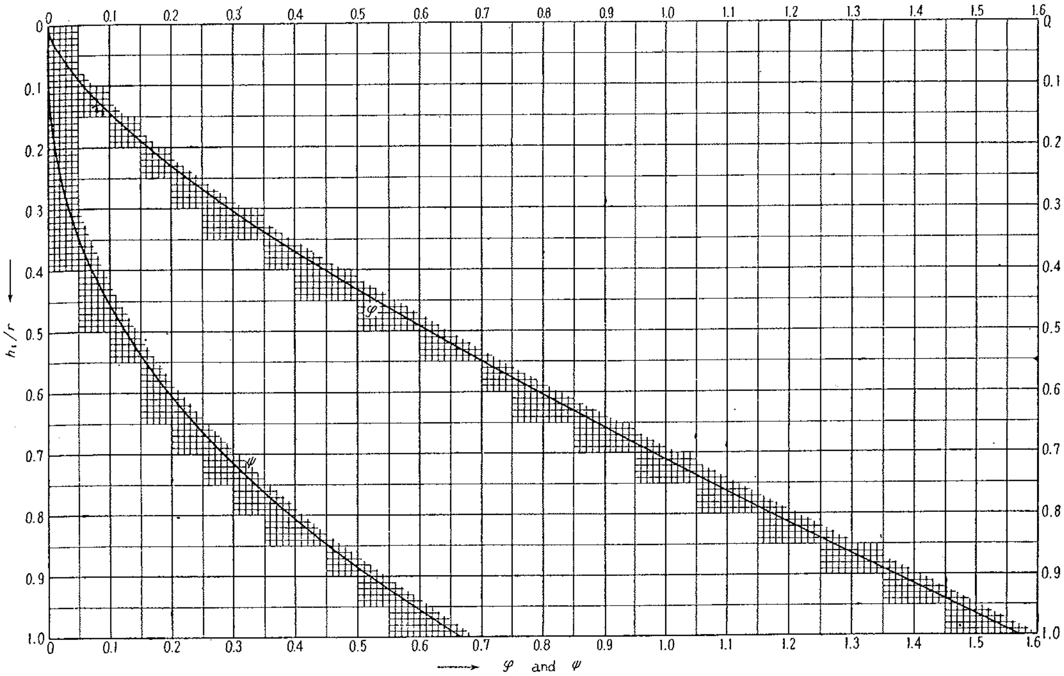
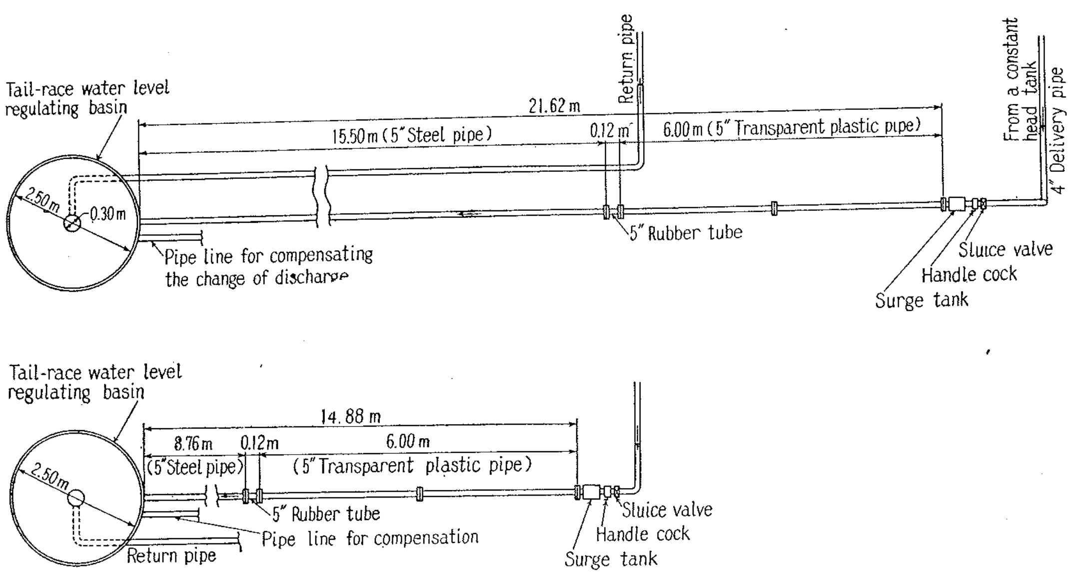


Fig. 6 Experimental installations.



$$\left.\begin{aligned} \frac{dv}{dt} &= \frac{z \mp cv^2}{L/g}, \\ \frac{dz}{dt} &= \frac{Q - fv}{F}, \end{aligned}\right\} \qquad \cdots\cdots (13)$$

which are the conventional surging equations for the simple surge tank except the differences at their signs.

EXPERIMENTAL INSTALLATIONS

At Chuo University two alternative pipe-lines have been installed, respectively 21.62 m and 14.88 m long and both nominally 5 inches (actually 13.07 cm) in diameter. The slopes of them are 1 : 1,000 and 1 : 420, respectively. Each 6 m long up-stream part of the pipe-lines consists of transparent pipe and the rest of galvanized steel pipe. Each pipe-line is set in a straight line. It commences with a surge chamber, to the up-stream part of which the supply pipe 4 inches in diameter from a constant head tank is connected (**Fig. 6**). At the supply pipe near the surge chamber a sluice valve having a handle cock down-stream is inserted. The rate of discharge is adjusted in advance of each test run by means of the sluice valve, the rejection of the discharge being done practically instataneously by means of the handle cock.

The main pipe-line terminates in a large basin 2.50 m in diameter, which is to keep any water level corresponding to any stage of water at the exit of the tail-race tunnel. The basin has, at its center, a spillway of adjustable elevation. To the basin another similar pipe-line is connected, which is operated as a pipe-line compensating the change of discharge to the basin, and the discharge probably being the cause of the change in level, although it may be slight, due to the limited area of the basin and the limited length of the center overflow.

A number of surge chambers are available with various shapes, most of which are made of transparent plastics. The height of surge is recorded by means of a float 8 cm in diameter and a recording drum rotating a revolution per minute.

COMPARISON BETWEEN THE THEORY AND THE EXPERIMENT

In order to check the fundamental equations (11), a few cases of surging waves are worked at by arithmetical integration of the equations (11), and then they are compared with those given by experiment. The cases dealt with are as follows:

	L (m)	d (m)	f (m^2)	F (m^2)	Q (l/s)	v (m/s)	h_f (m)	c (m/(m/s)^2)
Case 1	21.62	0.1307	0.01344	0.1143	4.09	0.304	0.0272	0.2935
Case 2	14.88	0.1307	0.01344	0.0364	4.07	0.303	0.0235	0.2561

The results of Case 1 and 2 are shown in **Fig. 7** and **Fig. 8**, respectively, where heavy lines represent results by experiment and light lines those obtained by arithmetical integration of eqs. (11). They show that the agreement between the theory and the experiment is very close for the basic assumptions at the derivation of the theory. Thus the experiment indicates that the eqs. (11) may practically be used with confidence as the fundamental equations for surging of the surge chamber of the tail-race tunnel.

CONCLUSION

This investigation leads to the following conclusions:

(1) The governing equations for surging at the surge chamber of the tail-race tunnel due to load rejection are given by equations (11), which hold after air is admitted into the

Fig. 7 Comparison between the theory and the experiment for Case 1.

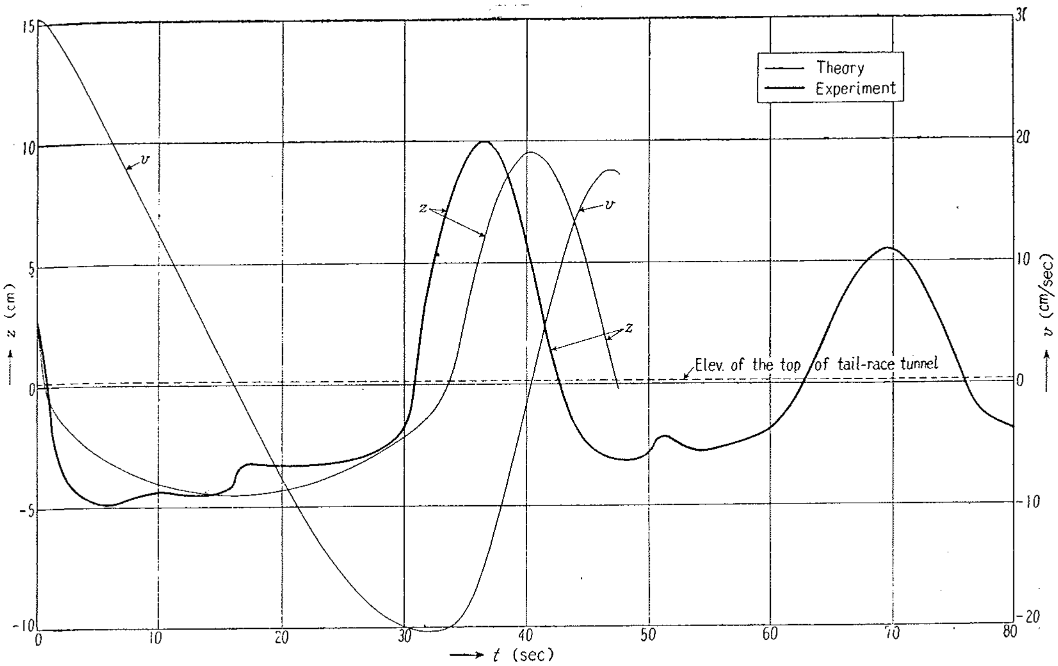
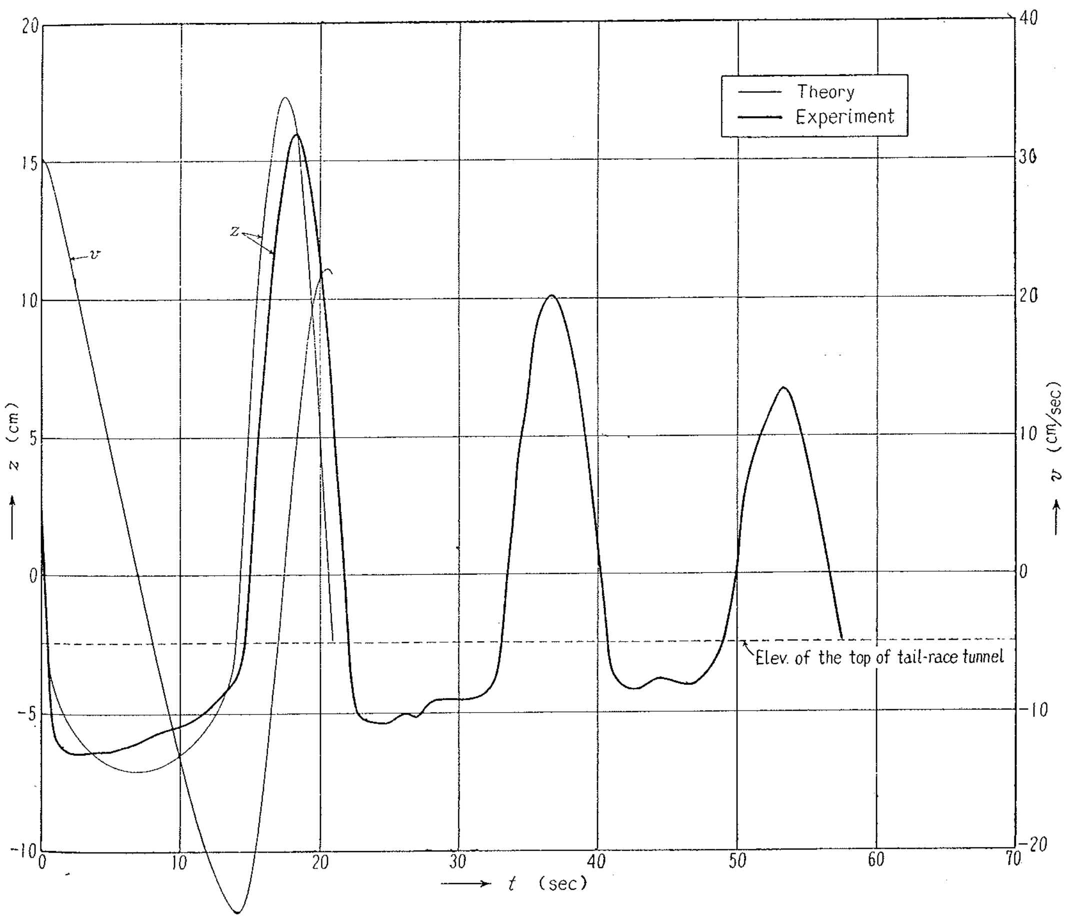


Fig. 8 Comparison between the theory and the experiment for Case 2.



tunnel as well as before air is admitted into it.

(2) By any proper method of integration of the equations (11) surging behavior of the surge-chamber of the tail-race tunnel due to load rejection can be analysed with confidence.

(3) The maximum rise of water level at the surge chamber is attained by the counter flow in the tail-race tunnel after load rejection. By any proper method of integration of the equations (11) the maximum rise which is an inevitable top surge can be calculated with confidence.

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Table 1 Numerical example of arithmetical

Basic equations			$\frac{dz}{dt}=\frac{Q-fv}{F+\frac{L}{h_1+h_2}\left(f'-\frac{V'}{L}\right)}$						$\frac{dv}{dt}=\frac{z\mp\left[cv^2\Big/\left(1-\frac{V'}{Lf}\right)\right]}{L/g}$						
Fundamental numerical values			$f=37.393\ m^2$, $F=450.000\ m^2$, $L=1200.000$ m						$c=0.1445\ m/(m/s)^2$, $L=1200.000$ m, $L/g=122.45\ s^2$						
Terms	t	Q	fv	$Q-fv$	$F+\frac{L}{h_1+h_2}\cdot\left(f'-\frac{V'}{L}\right)$	$\frac{dz}{dt}$	Δz	z	v^2	cv^2,	$\frac{cv^2}{1-\frac{V'}{Lf}}$	$z\mp\frac{cv^2}{1-\frac{V'}{Lf}}$	$\frac{dv}{dt}$	Δv	v
Units	s	m^3/s	m^3/s	m^3/s	m^2	m/s	m	m	$(m/s)^2$	m	m	m	m/s^2	m/s	m/s
	−0	120	120					1.488		1.488					3.209
	+0	0	120	−120	450	−0.267		1.488	10.30	1.488	1.488	0	0		3.209
	1	0	120.0	−120.0	450	−0.267	−0.267	1.221	10.30	1.488	1.488	−0.267	−0.0022	0	3.209
	2	0	119.8	−119.8	450	−0.266	−0.534	0.954	10.27	1.484	1.484	−0.530	−0.0043	−0.004	3.205
	3	0	119.7	−119.7	450	−0.266	−0.266	0.688	10.25	1.481	1.481	−0.793	−0.0065	−0.004	3.201
	4	0	119.4	−119.4	450	−0.265	−0.532	0.422	10.19	1.472	1.472	−1.050	−0.0086	−0.013	3.192
	5	0	119.0	−119.0	450	−0.264	−0.265	0.157	10.13	1.464	1.464	−1.307	−0.0107	−0.009	3.183
	6	0	118.6	−118.6	450	−0.264	−0.528	−0.106	10.06	1.454	1.454	−1.560	−0.0127	−0.021	3.171
	7	0	118.1	−118.1	450	−0.262	−0.264	−0.370	9.97	1.441	1.441	−1.811	−0.0148	−0.013	3.158
	8	0	117.5	−117.5	551.6	−0.213	−0.524	−0.630	9.87	1.426	1.426	−2.056	−0.0168	−0.030	3.141
	9	0	116.8	−116.8	853.0	−0.137	−0.213	−0.843	9.76	1.410	1.412	−2.255	−0.0184	−0.017	3.124
	10	0	116.1	−116.1	908.0	−0.128	−0.274	−0.904	9.64	1.392	1.395	−2.299	−0.0188	−0.037	3.104
	11	0	•	•	•	•	−0.128	−1.032	•	•	•	•	•	−0.019	3.085

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APPENDIX

By Pressel's method of arithmetical integration (cf., e.g., Ch. Jaeger: Technische Hydraulik (Verlag Birkhauser, Basel), 1949, S. 183) eqs. (11) are numerically integrated as in Table 1. The case dealt with is that of an instataneous total rejection of load. Based on the fundamental numerical values and the figures in block letters, calculations are proceeded with.

integration of the new governing equations (11).

$f'=r^2\varphi \qquad V'=\frac{L}{h_1+h_2}r^3\psi \qquad \varphi$ and ψ by Fig. 5

$a_1=-0.500$ m, $h_2=1.700$ m, $r=3.450$ m, $r^2=11.90$ m², $r^3=41.06$ m³, $L=1200.000$ m, $f=37.393$ m²

$h_1=a_1-z$	$\frac{h_1}{r}$	φ	ψ	f'	h_1+h_2	$\frac{L}{h_1+h_2}$	$r^3\varphi$	V'	$\frac{V'}{L}$	$\frac{V'}{Lf}$	$1-\frac{V'}{Lf}$	$f'-\frac{V'}{L}$	$\frac{L}{h_1+h_2}\left(f'-\frac{V'}{L}\right)$
m				m²	m		m³	m³	m²			m²	m²
0.130	0.038	0.013	0	0.155	1.830	655.7	0	0	0	0	1.0000	0.155	101.6
0.343	0.099	0.058	0.002	0.690	2.043	587.4	0.082	48.17	0.0401	0.0011	0.9989	0.686	403.0
0.404	0.117	0.074	0.004	0.881	2.104	570.3	0.164	93.53	0.0779	0.0021	0.9979	0.803	458.0
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要　　旨

放水路にすべて圧力がかかつた状態で水車運転が行われている場合にも，水車使用水量の変動により生ずる放水路サージ チャンバーの下降サージング時には，一般に放水トンネル内にも自由水面が侵入してゆき，そのような場合のサージングの計算には通常の導水路サージ タンクのサージングの基本式をそのままは適用することができなくなる。この場合の放水路内のサージング現象は複雑な波動現象と考えられるが，本論文においてはそのような複雑な波動現象としての取り扱いを避け，従来の導水路サージ タンクのサージングの基本式を，若干の仮定により修正して，そのような場合においても成立つべき基本式を誘導した。この新らしい基本式を適当な方法によつて積分することにより，放水路サージ チャンバーのサージングが解析される。特に水車発電機の負荷急遮断時の下降サージにともない，その揺れ戻しの段階において生ずるサージ チャンバーの上昇サージは，放水路のサージ チャンバーにおける避け得ざる一つの最上昇サージを与えるものとして，この揺れ戻しの最上昇サージを計算上の注目すべき一つの対象と考えた。

この基本式の妥当性の検討のために実験を行い，この基本式の数値積分により求められるサージング曲線と実験によるサージング曲線との比較を行つた。これによれば両者の一致の度合はほとんど十分なものであつて，新らしい基本式は放水路サージ チャンバーのサージング計算には，十分の信頼度をもつて使用しうるものであることが示された。

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