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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

ETL 1110-2-307

Technical Letter
No. 1110-2-307

20 August 1987

Engineering and Design
FLOTATION STABILITY CRITERIA FOR
CONCRETE HYDRAULIC STRUCTURES

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Report Documentation Page		
Report Date 20 Aug 1987	Report Type N/A	Dates Covered (from... to) -
Title and Subtitle Engineering and Design: Flotation Stability Criteria for Concrete Hydraulic Structures	Contract Number	
	Grant Number	
	Program Element Number	
Author(s)	Project Number	
	Task Number	
	Work Unit Number	
Performing Organization Name(s) and Address(es) Department of the Army U.S. Army Corps of Engineers Washington, DC 20314-1000	Performing Organization Report Number	
Sponsoring/Monitoring Agency Name(s) and Address(es)	Sponsor/Monitor's Acronym(s)	
	Sponsor/Monitor's Report Number(s)	
Distribution/Availability Statement Approved for public release, distribution unlimited		
Supplementary Notes		
Abstract		
Subject Terms		
Report Classification unclassified	Classification of this page unclassified	
Classification of Abstract unclassified	Limitation of Abstract UU	
Number of Pages 15		

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Engineering and Design
FLOTATION STABILITY CRITERIA FOR
CONCRETE HYDRAULIC STRUCTURES

1. Purpose. This ETL provides guidance for evaluating flotation stability of concrete hydraulic structures.
2. Applicability. This ETL applies to all HQUSACE/OCE elements and field operating activities having civil works responsibilities.
3. References.
 - a. EM 1110-2-2200, "Gravity Dam Design."
 - b. ETL 1110-2-256, "Sliding Stability for Concrete Structures."
4. Discussion. Hydraulic structures, such as U-frame locks, stilling basins, pumping stations, conduits, canal linings, and spillway sills and aprons, are subjected to buoyant forces which affect structural stability. This ETL provides guidance for determining if the structures are adequately stable with respect to buoyant forces.
5. Flotation Safety Factor. The flotation safety factor, SF_f , is defined as:

$$SF_f = \frac{W_s + W_c + S}{U - W_g} \quad (1)$$

where W_s = Weight of the structure, including weights of fixed equipment and soil above the top surface of the structure. The moist or saturated unit weight should be used for soil above the groundwater table and the submerged unit weight should be used for soil below the groundwater table.

W_c = Weight of the water contained within the structure which is controlled by a mechanical operator (i.e., a gate, valve, or pump).

S = Surcharge loads.

U = Uplift forces acting on the base of the structure.
The uplift forces should be calculated in accordance
with References 3a and 3b.

W_g = Weight of surcharge water above top surface
of the structure which is totally controlled by
gravity flow.

When calculating SF_f , the vertical resistance mobilized by
friction along the exterior faces of the structure should be
neglected. The basic assumptions and general derivation of
flotation safety factor are given in Enclosure 1.

6. Flotation Stability Criteria. Concrete hydraulic structures
should be designed to have the following minimum flotation safety
factors:

Loading Conditions	Minimum SF_f
Construction	1.3
Normal Operation	1.5
Unusual Operation	1.3
Scheduled Maintenance (e.g., structure dewatered with normal tailwater or normal lower pool)	1.3
Extreme Maintenance (e.g., structure dewatered with maximum tailwater or maximum lower pool)	1.1

Any relaxation of these values will be accomplished only with the
approval of HQUSACE (CEEC-ED) and should be justified by a
comprehensive study of the piezometric pressure data and
engineering properties of the structure, foundation and backfill.

7. Design Examples. Design examples for calculating the
flotation safety factors are contained in Enclosure 2.

FOR THE COMMANDER:

2 Enclosures



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BASIC ASSUMPTIONS AND DERIVATION OF FLOTATION SAFETY FACTOR

1. Definitions and Symbols

SF_f = Flotation safety factor.

W_s = Weight of the structure, including weights of fixed equipment and soil above the top surface of the structure. The moist or saturated unit weight is used for soil above the groundwater table and the submerged unit weight is used for soil below the groundwater table.

W_c = Weight of the water contained within the structure which is controlled by a mechanical operator (i.e., a gate, valve, or pump).

W_g = Weight of water above the top surface of the structure which is totally controlled by gravity flow.

S = Surcharge loads.

U = Uplift forces acting on the base of the structure.

N = Normal component of the base reaction.

L = Length of the base.

H_u, H_b = Lateral hydrostatic forces.

T = Tangential component of the base reaction.

p_u, p_d = Uplift pressure heads.

2. Basic Assumptions and Simplifications

a. The structure is a rigid and impermeable mass.

b. A mathematical definition of flotation safety factor should satisfy the equation of vertical equilibrium.

c. Flotation occurs when the normal component of the base reaction, N , is equal to zero.

d. Flotation is a state of neutral equilibrium which is independent of the submergence depth. Therefore, the flotation safety factor is also independent of the depth of submergence over the structure.

e. Water which is contained within the structure should be treated as an additional weight. (This is why damaged ships sink as the interior is flooded).

f. The flotation analysis is only uncoupled from the stability analysis if the location of the loading resultant is within the kern of the base. If the resultant is not within the kern, the uplift pressure distribution should be modified over the portion of the base which is not in compression.

3. Derivation of Flotation Safety Factor

The generic geometry and loading conditions are shown in Figure 1-1.

From Figure 1-1, the vertical equilibrium of the structure can be expressed as:

$$N + U - W_s - W_c - W_g - S = 0 \quad (1-1)$$

As discussed in Paragraph 2 above, a flotation safety factor, SF_f , should satisfy the following basic conditions:

(a) SF_f should be independent of the submergence depth.

(b) Water contained within the structure should be treated as additional weight.

(c) $SF_f = 1$ if $N = 0$

The equilibrium equation (1-1) can be rewritten to satisfy conditions (a) and (b) as:

$$N + (U - W_g) = W_s + W_c + S \quad (1-2)$$

The SF_f can be defined to satisfy condition (c) as:

$$SF_f = \frac{N + (U - W_g)}{U - W_g} \quad (1-3)$$

Substituting Eq. (1-2) into Eq. (1-3), we get

$$SF_f = \frac{W_s + W_c + S}{U - W_g} \quad (1-4)$$

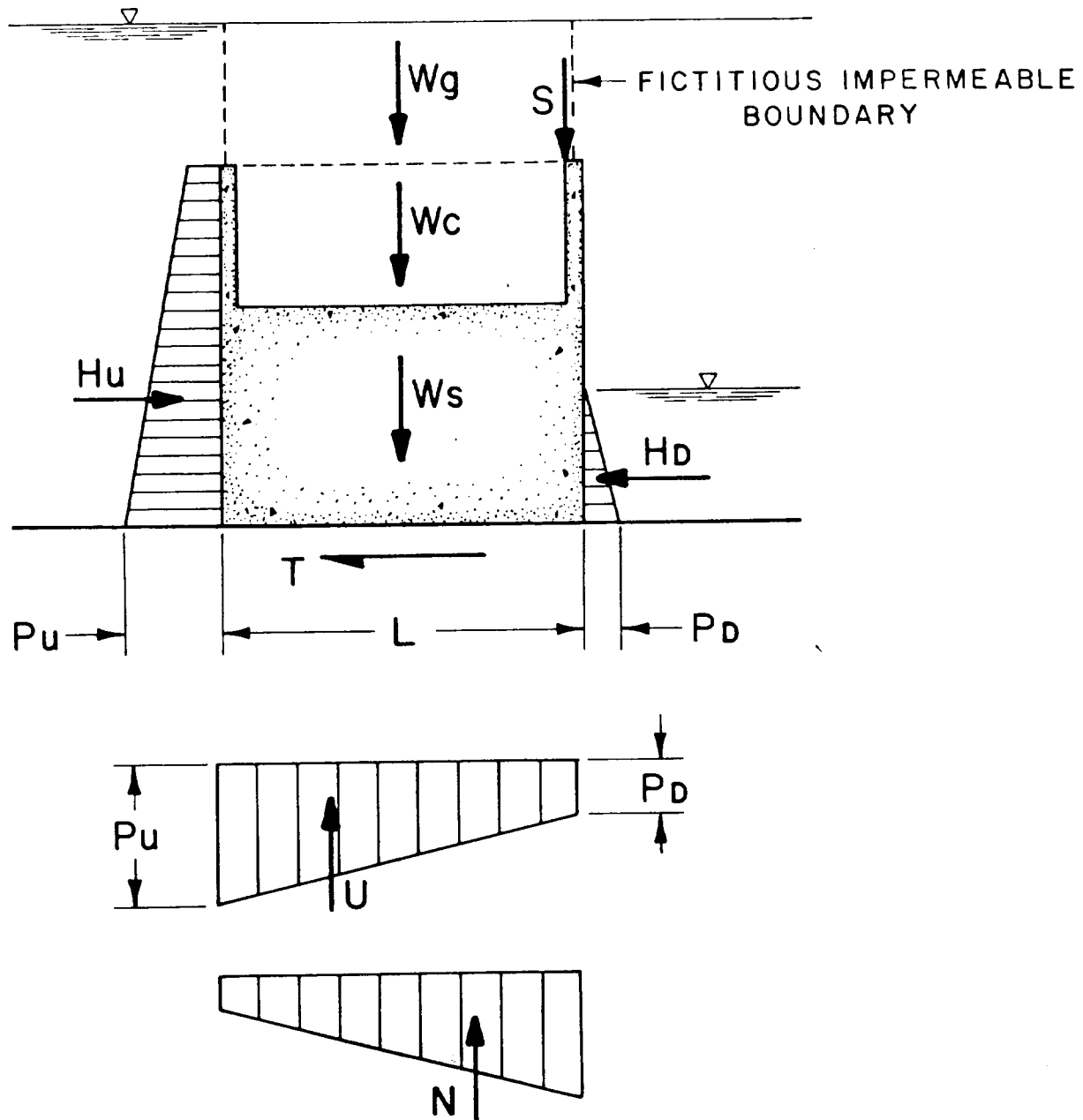


Figure 1-1 Generic Geometry and Loading Conditions

DESIGN EXAMPLES

1. DESIGN EXAMPLE 1 - U-FRAME LOCK

A. Design Conditions

In this design example, two loading conditions are illustrated:

CASE I: Normal Operating Condition

- a. Upper pool elevation - 95.0 ft
- b. Lower pool elevation - 64.0 ft
- c. Lower pool in lock chamber

CASE II: Extreme Maintenance Condition

- a. Upper pool elevation - 95.0 ft
- b. Lower pool elevation - 81.0 ft
- c. Lock chamber dewatered

B. Structural Dimensions and Loading Conditions

The structural dimensions and loading diagrams are shown in Figure 2-1. The loads are tabulated in Table 2-1.

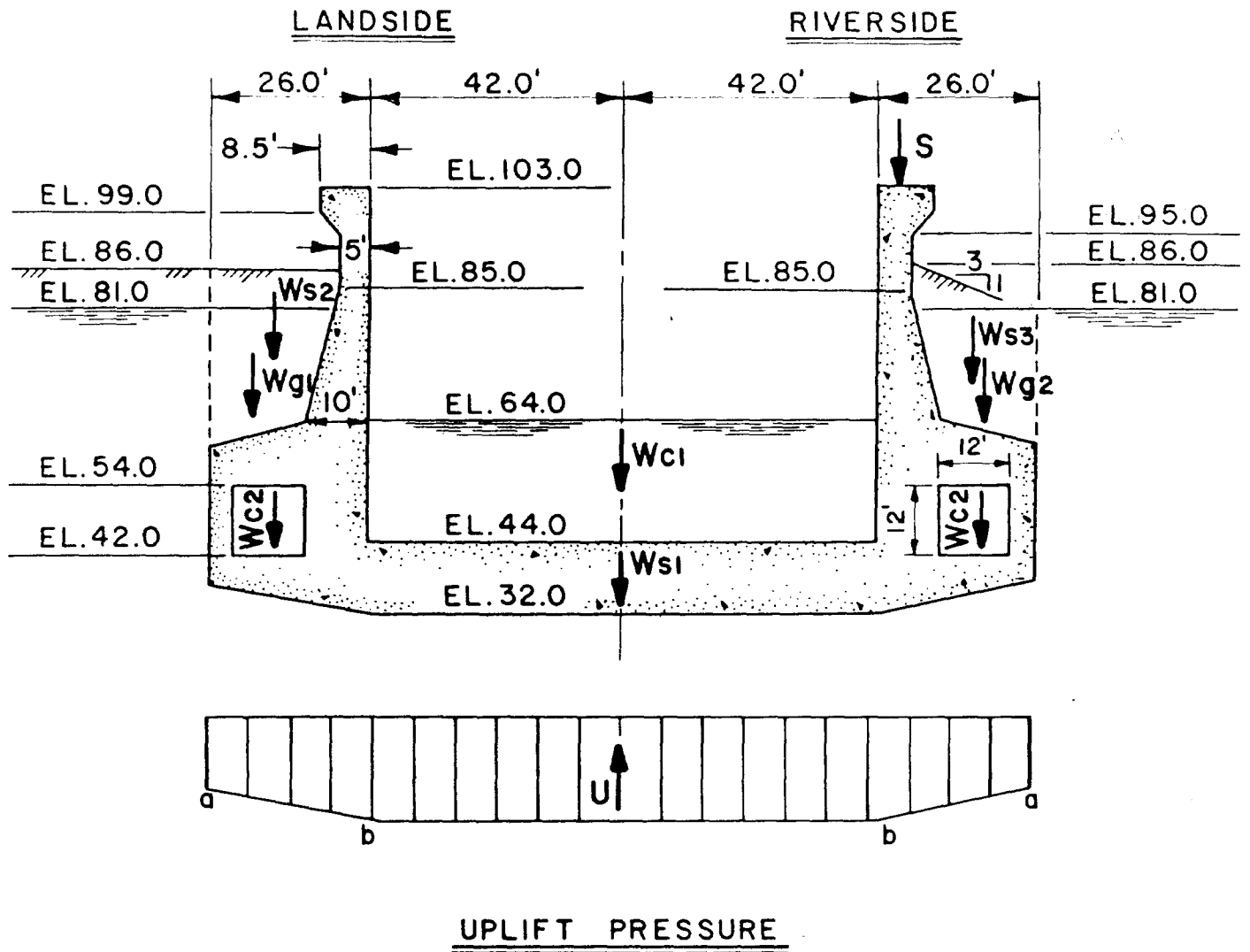


Figure 2-1 Structural Dimensions and Loading Diagrams

Table 2-1 Summary of Loads

Loads	Loading Conditions*	
	CASE I	CASE II
Weight of the structure, W_{s1}	407.7	407.7
Weight of soil above the lock on landside, W_{s2} #	36.2	36.2
Weight of soil above the lock on riverside, W_{s3} #	24.8	24.8
$W_s = W_{s1} + W_{s2} + W_{s3}$	468.7	468.7
Weight of water in lock chamber, W_{c1}	105.0	0
Weight of water in culvert, W_{c2}	18.0	0
$W_c = W_{c1} + W_{c2}$	123.0	0
Weight of water above the lock on landside, W_{g1}	21.1	21.1
Weight of water above the lock on riverside, W_{g2}	17.6	17.6
$W_g = W_{g1} + W_{g2}$	38.7	38.7
Uplift pressure at point a (See Fig. 2-1)	2.44**	2.75**
Uplift pressure at point b (See Fig. 2-1)	3.09**	3.40**
Total uplift, U	365.9	454.3
Surcharge load, S	0	0

* All loads are in kips/ft except as noted

** Uplift pressures are in kips/sq ft

Saturated weight (130 lbs/cu ft) is used for soil above
EL. 81.0 and submerged weight (67.5 lbs/cu ft) is used for soil
below EL. 81.0

C. Flotation Safety Factors

The flotation safety factors can be calculated by substituting the appropriate loads from Table 2-1 into Equation (1) in the basic letter:

CASE I : Normal Operating Condition

$$\begin{aligned}
 SF_f &= \frac{W_B + W_C + S}{U - W_g} & (1) \\
 &= \frac{468.7 + 123.0 + 0}{365.9 - 38.7} \\
 &= 1.81 > 1.5 \quad \text{O.K.}
 \end{aligned}$$

CASE II: Extreme Maintenance Condition

$$\begin{aligned}
 SF_f &= \frac{W_B + W_C + S}{U - W_g} & (1) \\
 &= \frac{468.7 + 0 + 0}{454.3 - 38.7} \\
 &= 1.13 > 1.1 \quad \text{O. K.}
 \end{aligned}$$

2. DESIGN EXAMPLE 2 - STILLING BASIN

A. Design Condition

The water profile used for the unusual operating condition with one tainter gate half open is shown in Figure 2-2. The upper pool elevation is at EL. 95.0 and the tailwater is at EL. 64.0. The drain effectiveness for uplift calculation is assumed to be 50%.

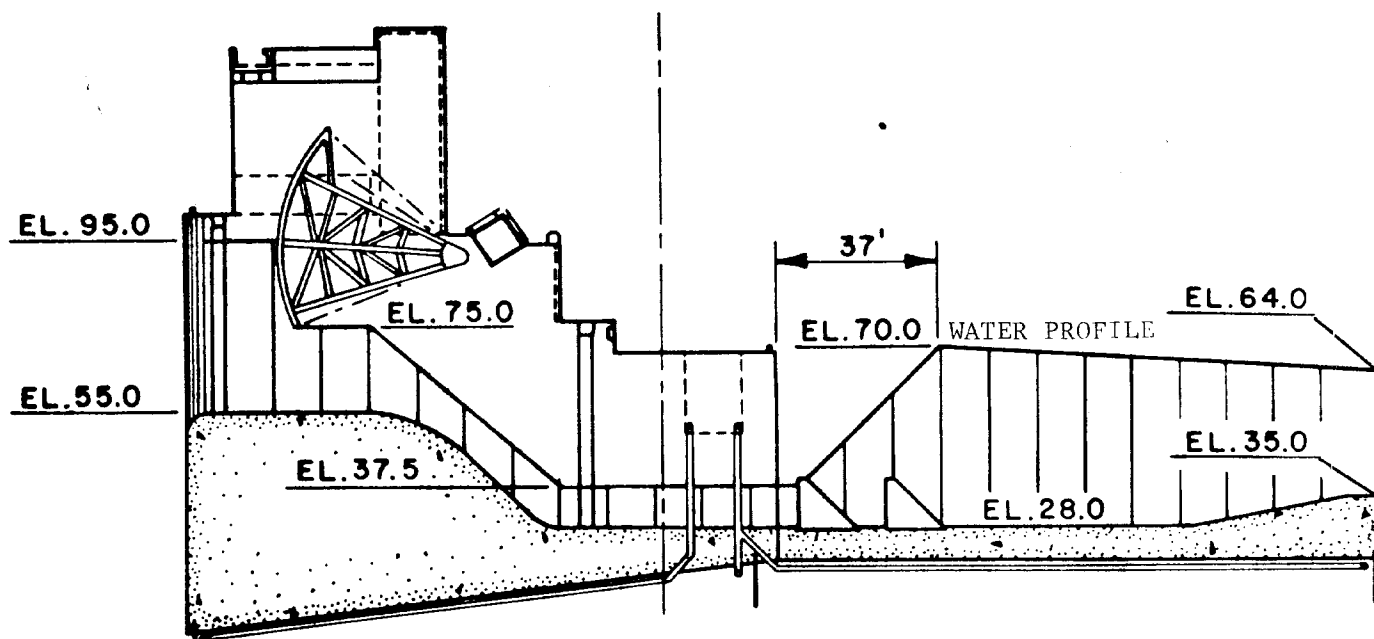


Figure 2-2 Stilling Basin Water Profile

B. Structural Dimensions and Loading Condition

The structural dimensions for the stilling basin are given in Figure 2-3.

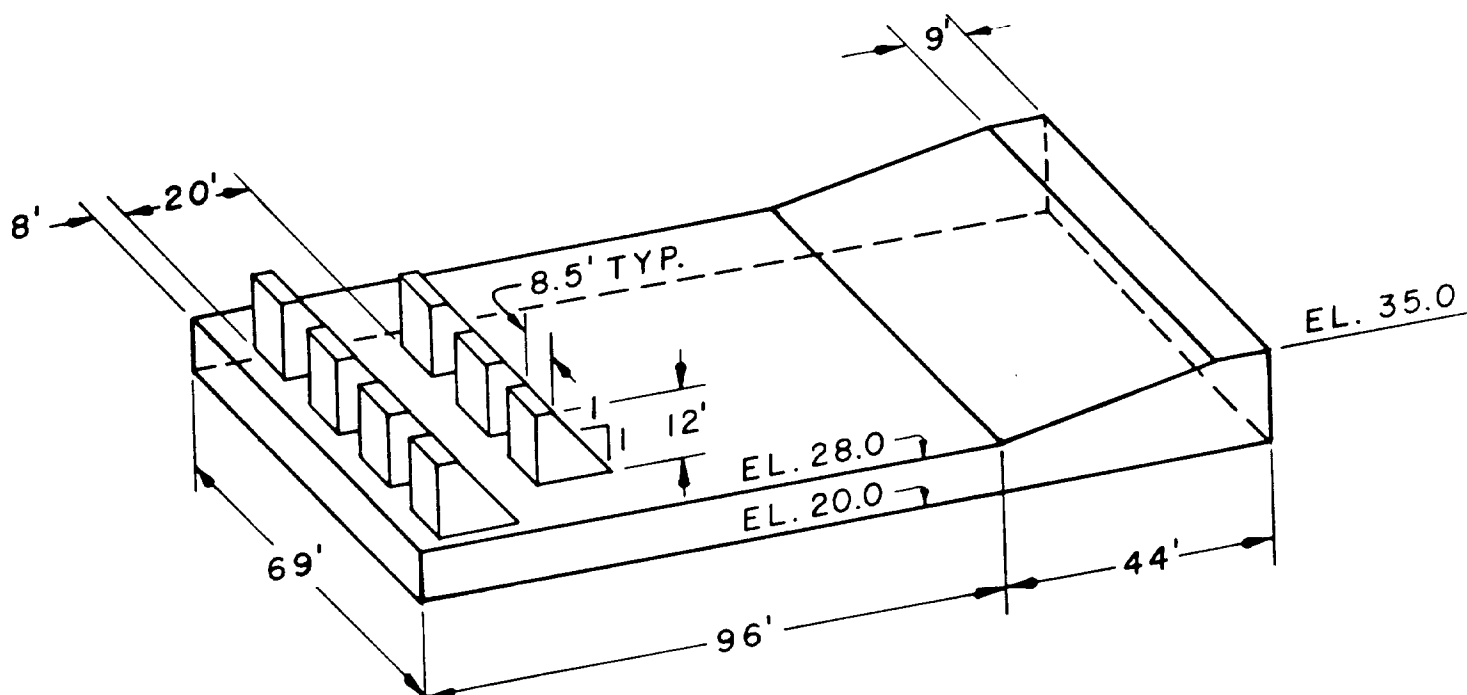


Figure 2-3 Structural Dimensions, Stilling Basin

The final loading condition is shown in Figure 2-4. It should be noted that, in this design example, the results of the stability analysis indicate that a portion of the stilling basin slab is not in compression. Full uplift force is applied for the portion of the slab that is not in compression and the final uplift distribution as shown in Fig. 2-4 is obtained through an iteration process. From the information given in Figs. 2-2, 2-3, and 2-4, it can be shown that:

W_s = Weight of the concrete stilling basin = 212.6 kips/ft
 W_c = Weight of the water contained in the basin up to
EL. 35.0
= 44.5 kips/ft
 W_g = Weight of the water above EL. 35.0 = 244.3 kips/ft
 U = Final uplift force = 441.2 kips/ft

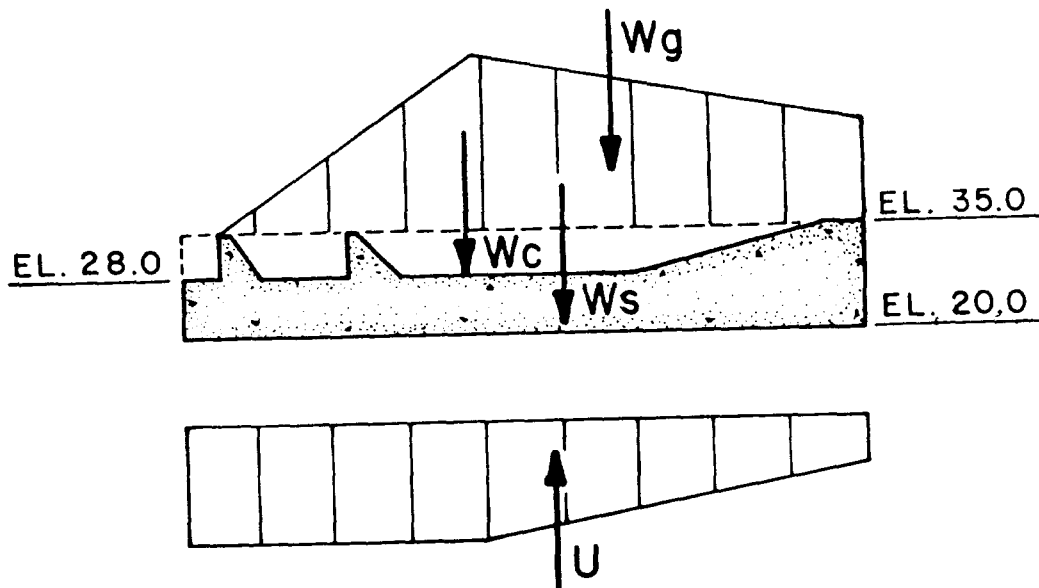


Figure 2-4 Loading Conditions, Stilling Basin

C. Flotation Safety Factor

The flotation safety factor can be calculated by substituting the loads into Equation (1) in the basic letter:

$$SF_f = \frac{W_s + W_c + S}{U - W_g} \quad (1)$$

$$= \frac{212.6 + 44.5 + 0}{441.2 - 244.3}$$

$$= 1.31 > 1.3 \quad \text{O. K.}$$

3. DESIGN EXAMPLE 3 - PUMPING STATION

A. Design Condition

The loading conditions for an unusual operation condition with water in sump at EL. 249.0 when pumps are shutoff are shown in Figure 2-5. The saturation line is at EL. 263.4 and moist fill is used above saturation line.

B. Structural Dimensions and Loading Conditions

The structural dimensions and loading diagrams are shown in Figure 2-5. It can be shown that

W_s = Weight of the structures

= $B + R + S_B + P + S.G. + V.P.$

where B , weight of the superstructure = 333.5 k

R , weight of the trash rack = 30.1 k

S_B , weight of the substructure = 2694.1 k

P , weight of the pumps, motors,
and equipment = 152.0 k

$S.G.$, weight of the switch gear = 17.2 k

$V.P.$, weight of the vacuum pump = 1.0 k

W_s = $333.5 + 30.1 + 2694.1 + 152.0 + 17.2 + 1.0$
= 3227.9 k

U = Uplift = 3080.6 k

W_c = Weight of the water contained within the
structure = 0 k

S = Surcharge loads = 0 k

Because of the open trash rack, the water in the sump is controlled by gravity flow, and therefore; weight of the water in the sump should be treated as W_g .

W_g = $45 \times 37.71 \times 6 \times 0.0625 = 636.36 \text{ k}$

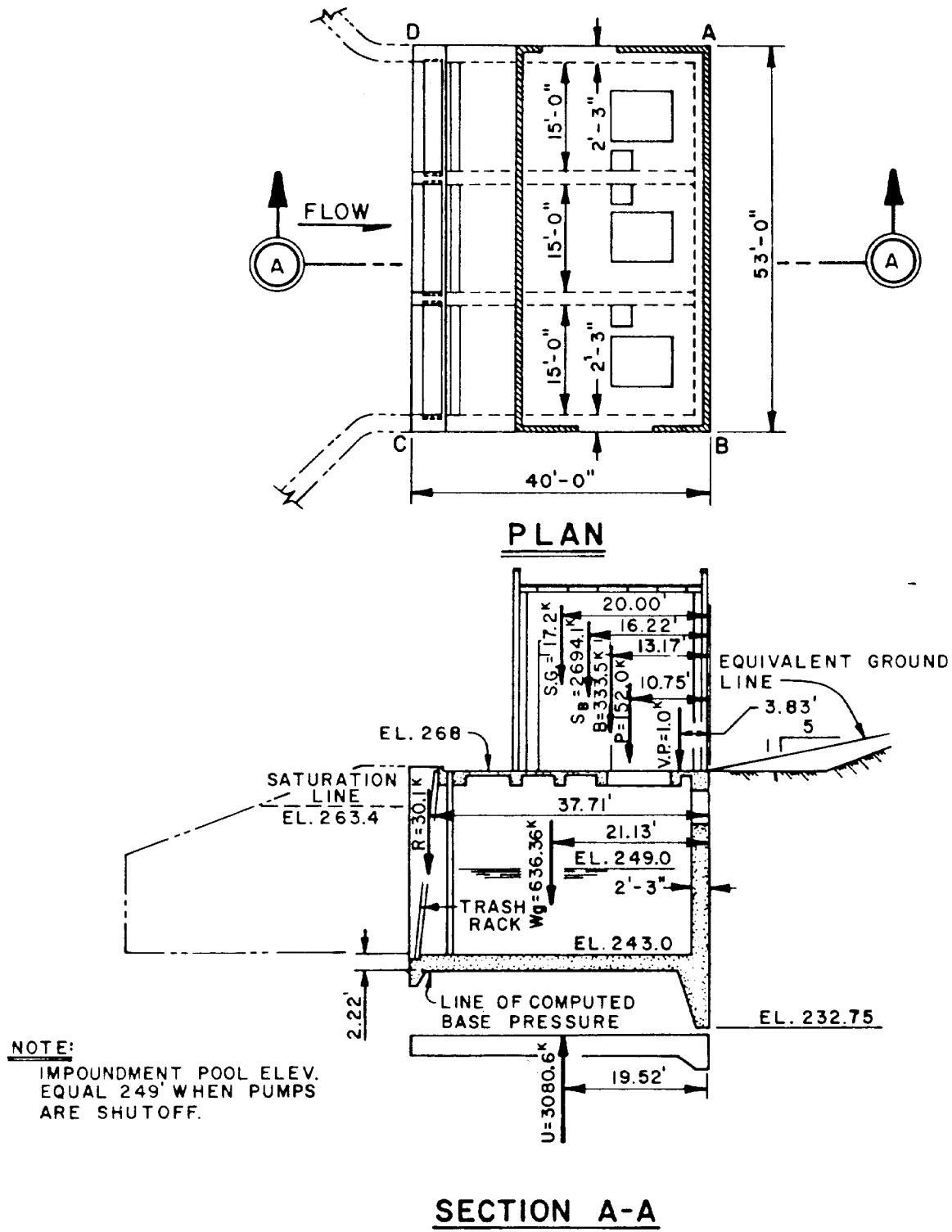


Figure 2-5 Pumping Station Dimensions and Loading Diagrams

C. Flotation Safety Factor

$$SF_f = \frac{W_s + W_c + S}{U - W_g} \quad (1)$$

$$\begin{aligned} & \frac{3227.9 + 0 + 0}{3080.6 - 636.36} \\ & = 1.32 > 1.3 \quad \text{O.K.} \end{aligned}$$