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Research Article

Examining the risk of flotation in structures

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ABSTRACT

Lately, an increase in the number of floors in structures that have been built on valuable land can be noticed. While building these structures, a retaining wall is created, which is necessary for a safe foundation, yet this also causes the formation of a closed pool-like area. If the excavation site during construction is filled with water due to various reasons, basement floors, which form closed volume, may move upwards. The same problem may also be experienced in all elements that are underground in flood susceptible areas. Unfortunately, engineers often overlook this potential problem while focusing on the completed structure weight. This flotation damage should not be confused with liquefaction of ground that occurs as a result of unexpected movements in the structure due to the loss of the bearing capacity of the ground. The necessary calculations to avoid this risk are only conditioned for port and coastal structures in national standards and codes. Hence, this study aims to demonstrate the conditions leading to flotation in structures and necessary precautions to avoid them.

1. Introduction

Engineers generally consider structure load on the vertical plane along with earthquake and wind forces on the horizontal plane in order to design a safe building effectively. In addition, since the 1995 Kobe earthquake, earthquake engineers have to focus on the vertical force on the structure resulting from an earthquake [1]. Another factor that requires the attention of engineers to the vertical force on a structure is a tsunami [2, 3]. The tsunamis which happened in Peru in 1996; in Papa New Genia in 1998 and on the Sumatra Island in Indonesia in 2004 caused buildings to float easily. The earthquake measuring 9 Mw and the tsunami in Tōhoku area in Japan on March 11, 2011 resulted in significant economic damage as well as 15.828 casualties except for the missing [4]. After the earthquake, tsunami waves reaching heights of up to 3 - 37.9 meters occurred in the area [5]. During tsunamis, structure weight remains insufficient to resist the static and dynamic effect of water (Figure 1).

There are instances other than tsunamis in which water impacts structures such as spates and overflows, tidewater from the sea, river flooding due to unexpected level of water, excessive and fast water or mud flow due to heavy and severe rainfall, flood and/or high level of underground water (UWL) cause structures to submerge, which becomes another issue that engineers should be careful about (Figure 2).

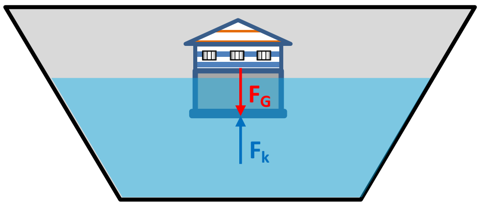

Figure 1. Structure floats when the weight of a structure (F_G) exceeds the buoyancy force (F_k) [6]

Lately, many structures in Turkey and abroad have been flooded due to the reasons mentioned above (Figure 2). Overflows are not the only reason for the submergence on the coastlines or riverbanks. Heavy and rapid rainfall, dam/aqueduct overflows, landslides and even burst water main may also lead to flooding on coastlines and riverbanks as well as in the interior parts. Floods and overflows might be destructive; since they expose structures to impact loads and leave submerged structures open to vast and intense loads. Even though these serious impacts are taken into account for stability

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(a) (b)

Figure 2. City centers that experienced floods, spates and overflows a) [7], b) May 2017, İzmir

of offshore structures and pipelines [8-10], they are not equally considered while designing structures on land.

It has been stated that nearly 90% of the property damage including the damage to the mechanical and electrical devices in the U.S. has been resulted from the overflows causing economic damage worth 3.5 million dollars annually on average [11, 12]. During storms, the water level which structures are in rises even more when wind pushes water to the shore. For example, the hurricanes Andrew, Hugo, Charley, Katrina and Rita have been found to increase the damage even more. However, the scope of this study will be the physical process, floating damage and the economic loss in structures/structure elements resulting from floods, spates and overflows as well as necessary precautions against them.

2. Forces Impacting Structures

Since floods and overflows are not generally expected inlands, the risk is often ignored during design and construction processes. However, heavy and rapid rainfall, fast melting of snow/ice, dam/aqueduct overflows, over-capacity drains and even burst water main might lead to floods and thereby submerged structures.

Three physical forces mostly impact structures affected by flood and overflow, which are hydrostatic (Figure 3a-c), hydrodynamic and impact loads. In addition to these loads, soil effects around and below foundation may worsen the condition of a structure.

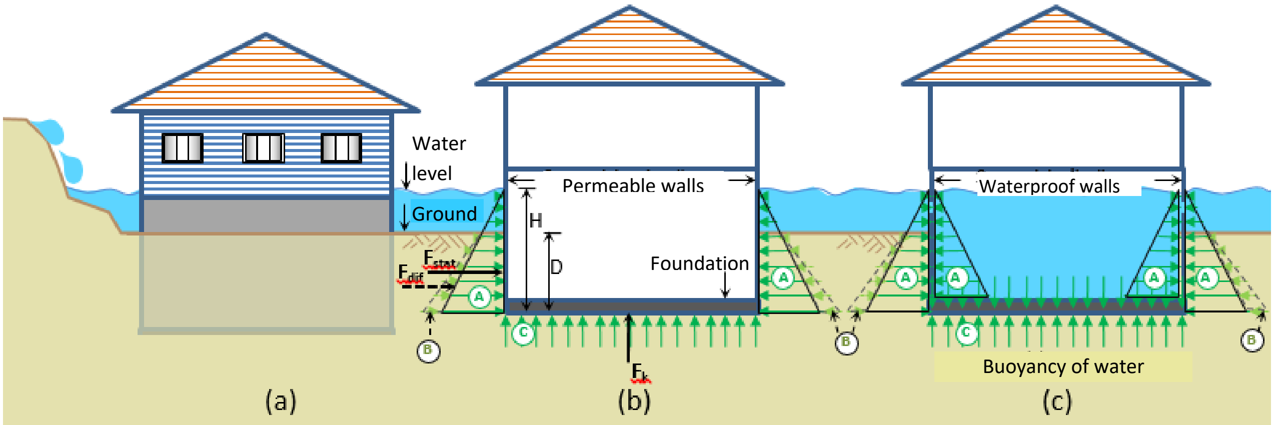


Figure 3. Hydrostatic and earth pressure forces affecting the structure a) structure affected by an overflow, b) waterproof basement walls, c) permeable basement walls

Hydrostatic loads are both lateral (pressure) and vertical (flotation) effects that arise when a structure is surrounded with water (Figure 3b-c). Hydrostatic loads are both lateral (pressure) and vertical (flotation) effects that arise when a structure is surrounded with water (Figure 3b-c).

Hydrostatic forces seen in Figure 3 which are lateral water pressure F_{stat}, lateral differential waterlogged soil pressure F_{dif}, and vertical (flotation) water pressure F_k can be calculated as shown below:

Ⓐ → Lateral Water Pressure: $F_{stat} = \frac{1}{2}\,\gamma_{water}\,H^2$ (1)

Ⓑ → Lateral Differential Water and Soil Pressure:

$$F_{dif} = \frac{1}{2}\,(S - \gamma_{water})\,D^2 \quad (2)$$

Ⓒ → Vertical Water Pressure: $F_k = \gamma\,(Vol)$ (3)

Here; γ_{water} is the specific weight of water (fresh water: 1 kg/m^3 and salty water: 1.025 kg/m^3); H is the distance between structure's ground and level of water (m); S is the equivalent fluid weight of waterlogged soil and water (kg/m^3); D is the vertical distance between the structure's ground and earth level (m); Vol is the volume of submerged part of the structure (m^3).

Lateral forces result from the difference in height between water level inside and outside. When the floodwater outside a structure rises, pressure affects the walls of the structure inward (Figure 3b); when the structure is filled with water, internal and external forces even up each other (Figure 3c); and when the floodwater outside the structure subsides, pressure outward arises from the walls of the structure.

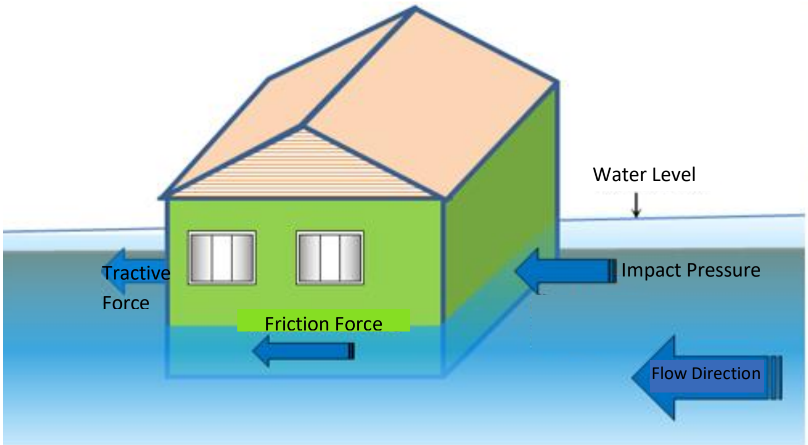
Lateral hydrostatic forces are not enough to cause deformation of a structure element or displace a structure unless there is a great difference in the level of water outside and inside of a structure (Figure 3b-c). Ensuring that the floodwater in the basement gets through the other side of the structure stabilizes hydrostatic balance mutually. If bearing elements are not strong enough, lateral hydrostatic pressure may cause permanent misalignments and damage structural elements. If there is a rapid increase or decrease in the level of water inside and outside of a building whose walls are not strong enough, the emerging difference may damage the walls or the foundation. However, when the level of water inside and outside evens up, this force disappears (Figure 3c). In other words, potential damage due to lateral pressure in a water-permeable building would be low. It should not be forgotten that if the floodwater inside a building is pumped out to the waterlogged soil, lateral pressure may arise again towards the basement walls which may be damaged by collapsing inward due to exceeding the structural capacity.

Vertical hydrostatic forces are not risky for safely-built structures. Yet, when a basement floor, an enclosed volume, is submerged during construction, buoyancy force may be worrisome if the vertical hydrostatic force exceeds the structure weight (Figure 1, 3b-c).

During a flood, the water flowing around a structure creates hydrodynamic and impact loads on the structure (Figure 4a). Lateral hydrodynamic force (F_{dyn}) is calculated as follows [13]:

$$\text{Lateral Drag Force: } F_{dyn} = C_d \, \rho \, V^2/2 \, A \qquad (4)$$

Here, ρ is the specific gravity of water; V is the velocity of flowing water, A is the surface area in the direction of flow; C_d is the resistance coefficient against drag, which depends on the width and the depth of a structure against water.
While floodwater is flowing around a structure, friction at the structure's side elements, front impact in the direction of surface flow and absorption at the back side of the structure are the hydrodynamic loads (Figure 4a). Especially when lateral hydrodynamic pressure, which increases in parallel with the intensity of water, is combined with impact loads, it may be damaging, destructive and/or overturning for structural elements (Figure 4b).



(a)

(b)

Figure 4. a) Hydrodynamic and impact loads, b) overturning of the structure due to these loads [13]

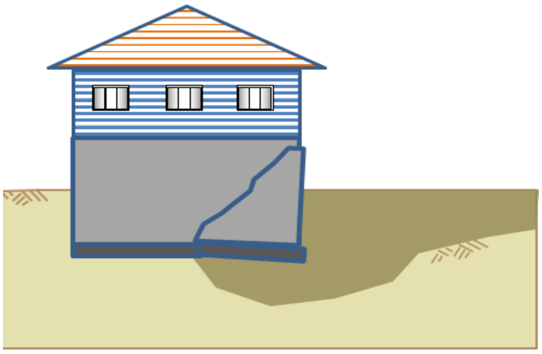
3. Other Impacts

In addition to the direct physical forces on the structure, fast-flowing water may worsen the situation by wiping away the soil supporting the foundation. In a completed structure, another way to help decrease unbalanced lateral and vertical loads to walls and foundation is to tighten the fill area contacting the structure. Otherwise, the filling around the structure may suffer from partial or complete erosion with floodwater, which might bring about serious consequences (Figure 5a-b). Erosion of the soil the structure is on depends on several factors such as soil slope; soil's being sandy or soft silty, which may change the excavation speed and ease. If erosion occurs, it may decrease the bearing capacity of the structure and thereby causing structural elements to collapse partially or completely.

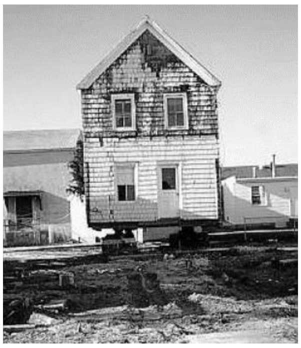
Also, unless liquid storage systems are designed to resist crushing pressure and buoyancy force, they may be susceptible to overflows.

While distribution pipes are closed pressure system that can relatively resist high exterior and interior pressures, liquid or fuel tanks are designed to resist only interior pressures, which may result in damage during overflows. Liquid tanks that are not specifically designed for the conditions during submergence may be crushed when exposed to exterior pressure. Several tanks/stores/manholes that are placed underground without any attachment (Figure 6a) may get damaged in various ways if they are subjected to intense water load (Figure 6b).

One may ask if there is another way to deal with hydrostatic and hydrodynamic forces in areas that are frequently exposed to floods and overflows. One way to avoid this situation is to prefer designing structures compatible with nature that can move up and down concurrently with the cycle of water rise. That's why, the research and construction of amphibious structures have been on the rise [9, 14]. Amphibious buildings are relatively cheap structures that can work with water and float up when needed, rather than resisting the forces induced by water. Amphibious structures are expected to move only vertically, which also means lateral movement is prevented (Figure 7a-c, 8).



(a)

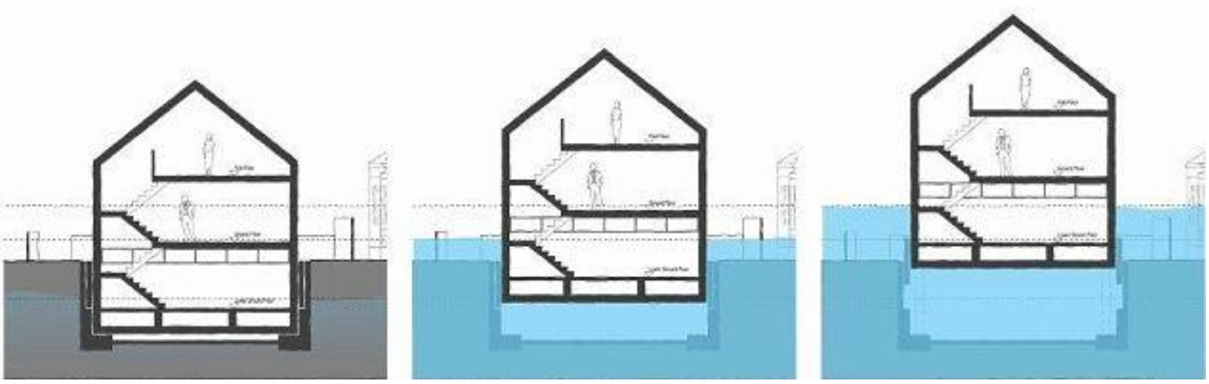


(b)

Figure 5.a, b) Soil loss due to water erosion

(a) (b)

Figure 6. a) Underground storage that can float up during an overflow, b) manhole that can move up with the vertical force of water [13]



(a) (b) (c)

Figure 7. Floating structures' a-c) up-down movement

Figure 8. Baca Architects ® practices

4. National/International Standards and Regulations regarding the Issue

When international publications are examined, various standards regarding the precautions against the hydrostatic and hydrodynamic effects of water on structures can be found [15-22]. To exemplify, according to Eurocode 1, 2.6. Section- 4.6., *"In case of exceedance of the water level stated in the project due to possible overflows or accidents during construction, static pressure, flotation and lateral forces may occur. Thus, these effects should be considered during design or precautions should be taken to prevent them*" [21]. According to Eurocode 7, 1. Section- 2.4.7.1., it should be confirmed with calculations that *"the limit of uplift movement of the structure due to buoyancy will not be exceeded"* [22]. Eurocode 7, 1. Section - 10.1. conditions that *"It should be certain that the structure will not move on account of buoyancy force"*. Also, in Eurocode 7, 1. Section- 12.5., it is stated that *"the possibility of flotation should be considered when light materials are used"*.

As for the national publications, in 2007 Specification for Buildings to be Built in Seismic Zones under the heading of Dynamic Active and Passive Earth Pressures, *" In addition to static earth pressure, additional dynamic active and passive earth pressure occurs in case of an earthquake and the change in this pressure through ground height*" is defined in equation in the Specification- 6.6 [22]. In the mentioned equation that gives active and passive pressure, "*if the ground is submerged, instead of γ (dry unit weight of the ground), γ_b will be taken into account; when the ground is waterlogged, instead of γ, γ_s (waterlogged unit weight of the ground) will be considered, and hydrodynamic pressure of water will also be calculated"*. Moreover, in the Bridge Design Principles published by the Ministry of Transportation, it is stated that "every element that is submerged will be taken into account as the buoyancy force comprising of static pressures" [24]. In another study regarding port structures, vertical and inertia forces have been defined [25]. A regulation dated 18.08.2007 and numbered 26617 has been issued to regulate necessary rules and minimum conditions to evaluate the earthquake performances of the present coastal-port, railway and airport structures as well as earthquake-resistant design of the ones that will be built, enlarged and changed in the future [26]. Under the head of 2.2.2.2.7 in the regulation, it is stated that *"buoyancy force will be considered only in vertical load combinations"* in port structures. There is also another study mentioning the principles published by the Ministry of Transport, Maritime and Communications that include coastal, port and marine structures [27]. As is seen, except for coastal, port and marine structures, there is no national regulation or standard stating that stability calculations of structures against flotation should be taken into account.

As a result of the examinations, on the national level, considering, analyzing and controlling the above-mentioned effect is only included in the technical specification published by Iller Bank [27]. In this specification, under the head of 2.6.2., it is stated *"flotation of structures will be checked depending on the level of underground water"*, and the head of 2.8.4.4. mentions *"stability analyses that call for the consideration of the most adverse water level and seismic loads during construction and use periods for the safety factors of overturning and flotation*". In the same specification, under the heads of 2.8.4.4.2 and 2.8.4.2.3, the condition of "consideration of stability calculations against flotation of a structure in case of elevation of surface or underground water or the elevation of both of those" is stipulated.

5. Precautions to be Taken

It will be useful to include the main points below for buildings other than coastal, port and marine structures in the national regulations and standards.

- Stability of structures should be ensured in a way to prevent flotation, collapse or lateral movement caused by hydrodynamic and hydrostatic loads including buoyancy effect.

- Engineers should make sure with calculations that all structural elements can resist hydrostatic and hydrodynamic forces including the buoyancy effect in a possible overflow. In this sort of calculations, moving load should not be included in the structure weight. Design load combinations should be evaluated by including overflows.
- If the structure weight remains insufficient to resist lateral and vertical buoyancy force of water, sufficiency of elements that can resist these forces (mechanical connections between the ground and foundation, lateral joint systems, tension piles etc.) should be demonstrated.
- It should be made sure that these forces should be considered not only for structures but also for all the elements that are underground (storages, tanks, manholes, etc.), and that materials which can resist these forces should be preferred.
- The soil or filling material on the bottom of and around a structure should be condensed that can resist erosion.

6. Conclusions

When national publications are analyzed, it is seen that the standards regarding the necessary precautions and design principles for hydrostatic and hydrodynamic effect of water on structures apply to port structures only. It is of utmost importance to include the conditions and guidelines regarding the stability calculations against flotation of all structures in national regulations and standards

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