Journals Pub

International Journal of
Geological and Geotechnical Engineering

ISSN: 2581-5598
Volume 11, Issue 2, 2025
July–December
DOI (Journal): 10.37628/IJGGE

https://journalspub.com/journal/ijgge/

Research IJGGE

Impact of Structural and Yielding Factors on Retaining Walls Behavior

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Abstract

Many factors are found to impact the behavior of retaining walls, RWs. These factors should be adopted in the design processes of these walls to satisfy the design requirements. They are linked to issues like structural behavior and yielding of the RWs. The major impacts of these factors are reviewed herein with some details. The reviewed factors exhibited that the yielding of RWs affects the design and modeling of RWs. The movement modes of these walls are related to their restraint condition under the different loading conditions. The shape of stress distribution due to lateral soil thrust behind RWs changes, according to the restraint degree, to produce a different resultant force with a centroid moved toward the middle of the wall. RWs prevented from movements need a higher safety factor against loading. Although greater lateral stability (against certain dynamic loads) can be attained by using heavier RWs, a negative effect on stability can occur by increasing the inertial forces of the wall due to earthquake loading. Well-designed walls to sustain the static loading are proven to ensure good performance of such a wall under dynamic loading, with PGA limited to 0.4 g, even when the seismic design is not considered. For RWs with an inclination toward backfill-side, some special considerations must be considered to avert the instability under earthquake shaking. For walls that derive their stability from the interaction between the soil and the mesh or strips included inside it, special measures related to the biological damage and environmental factors are necessary for structural stability.

Keywords: Interior stability, non-yielding, equilibrium mechanisms, seismic loading, retaining walls

INTRODUCTION

In practical geoengineering, the “lateral soil thrust, LST” is a crucial parameter for numerous engineering infrastructures. Many infrastructures are subject to LST from the various materials supported such as filling soil and earth banks, ore piles, grains, fill materials, water, etc. The geoengineering structures should be well-designed to sustain this pressure; such structures are retaining walls, RWs. These structures have a variety of applications in civil engineering fields like architectural, coastal, bridges, and road engineering [1–3]. The representative design and modeling of RWs absolutely depend on the technical knowledge in structural and geoengineering. Regard should be given to some important factors to ensure RWs’ typical modeling and design. Among these factors, RWs’ yielding, their structural behavior, equilibrium, and supporting mechanisms. Comprehension of the factors and impacts on RWs’ behavior is an extremely important issue for the economic and safety views [4–7].

In this sitting review, the impact of the mechanism to keep the lateral thrust of RWs within acceptable limits, their behavior to support different geomaterials, restraining (yielding), and keeping them in equilibrium is presented and debated.

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Received Date: August 12, 2025
Accepted Date: September 26, 2025
Published Date: September 27, 2025

Citation: Mahmood Ahmed, Abbas J. Al-Taie. Impact of Structural and Yielding Factors on Retaining Walls Behavior. International Journal of Geological and Geotechnical Engineering. 2025; 11(2): 9–19p.

RETAINING WALLS STRUCTURAL BEHAVIOR

As engineering structures, RWs can be constructed as a cantilever, or as anchored or strutted. Cantilever RWs symbolize structures that depend on stems (their cantilever action) to retain LST exerted by the geomaterials. These RWs are performed as fixed-cantilever columns, and they are convenient to retain filling up to 6.0 to 8.0 m; otherwise, they are uneconomical [8–11]. According to the structural design attitude, during the loading condition, cantilever RWs are subjected to shear force and moment on the base and stem. To reduce these forces on the RWs, additional structural members may be provided with additional structural members or modifications to assist the base and the stem, and to enhance efficiency. RWs can be provided with thin compressional members called "reverse-counterfort or buttress or reverse-counterfort" provided on the front side, or thin tension members called counterfort, on the backside. These members are constructed monolithically, regularly interval-spaced, with the base and the stem of the RWs (Figure 1). However, these members cause more difficulties and more complications in the RWs construction [8, 9].

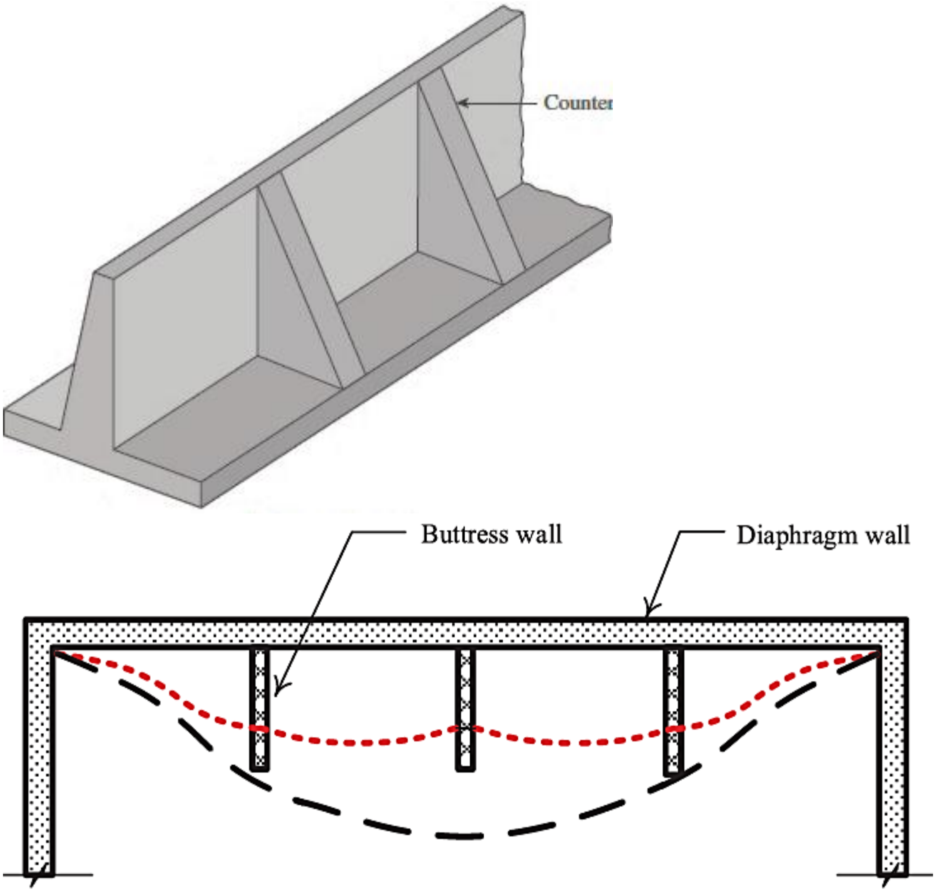

Figure 1. RWs with counterfort and reverse-counterfort [11, 12].

Another structural member can be provided to the stem and improve the structural behavior of the RWs, it is called "relief shelf" (Figure 2). The stem of RWs can be constructed with a monolithically single shelf or with multiple shelves. The role of these shelves is to reduce the LST and, as a result, minimize the shear and the moment of the RWs and increase the stability [13–18].

The base of the RWs, in turn, can be modified to improve the structural behavior of the RWs. They can provide keys, usually on the heel side of the base or beneath the RW center, to improve the resistance of the RWs to side forces and increase the passive force (Figure 3). However, the use of the bases with keys is influenced by the type of soil. They showed a good performance in the very stiff soils; otherwise, the use of the key may be subject to doubt [19–21].

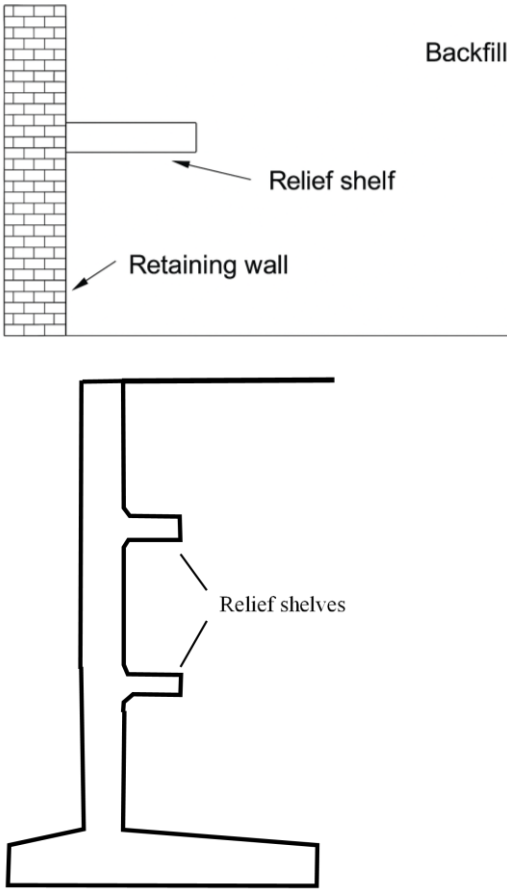

Figure 2. RWs with relief shelf [17, 18].

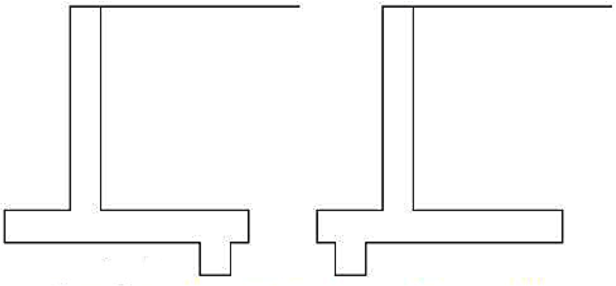

Figure 3. Retaining walls with a key.

The structural behavior of RWs may be influenced by the slope of the base and the heel slope. RWs with a base sloped from horizontal about 10°–15° show good stability compared to those with a flat base. The same merit has been proven for RWs with a heel sloped from vertically toward the backfill side [19, 22, 23]. For more structural stability, RWs should be designed with a proportional dimension. This case reduces the engineering efforts in the initial design stages. In fact, the dimensions of an RW are related to the wall's height as presented in Table 1.

Table 1. Proportioning RWs dimensions [11].

RW Components	**Approximate Dimension. m**
Base-width	(50%) to (70%) of the height.
Base-thickness	(10%) of the height.
Stem top-thickness	≥ 0.3 m.
Stem bottom-thickness	(10%) of the height.

On the other hand, the embedded RWs' bending capacity (like slurry RW, and secant pile and cantilever sheet-piles) has a great role in their structural stability [9, 24]. From an engineering view, these light RWs show good performance, minimum displacement, good capacity to support LST, and high stability when they are provided with anchors and props. The struts can be used to prove such stability when the site has a wide excavation area; otherwise, the anchors seem more suitable. The latter are more flexible as they can be constructed with different inclinations, and in single or multiple rows [24–27].

To ensure high structural behavior of anchors, a fulfiling safety factor is to be used in their design. The anchored RWs depend on their behavior of the anchor itself, and a front enlarged and passive wedge. So, to prevent them from combined the impact of the anchors' movement and the overturning of the base, the mentioned safety factor should be adopted. Furthermore, anchor movement after construction is a matter of interest, as it may cause severe damage. This movement produces a removal of the support for the wall. Meanwhile, the anchor length shows an important stability role under seismic loading; therefore, it should have been calculated well to achieve RWs under these loads [25, 28, 29].

RETAINING WALL YIELDING

The RWs are constructed either supported laterally at the top or not. The ones that supported laterally assume "stiff restraining", as "non-yielding", or "restrained", while the unsupported RWs assume "yielding". Figure 4 presents examples of non-yielding RWs, which include the bridge-abutment RWs, "cantilever side walls of the channels", basement RWs, tie-back RWs, and strutted RWs. According to Yi F (2013) [30], RWs that are constructed on stiff soil or rocks and show very small deflection (<2/1000 of RW height) are assumed non-yielding.

In the restrained RWs, the structural behavior differs from the yielding walls. The movement is not allowed; thus, the moment generated in the RWs is minimized. It is worth noting that a higher safety factor is required to prevent the movement of RWs. This means higher costs of walls, then leads to an uneconomical design state. Regarding the effect of restraint on the LST distribution, scholars stated that the well-known triangular distribution of LST changes from a linear classic form to a trapezoidal or non-linear shape. This, in turn, changes resultant force location, which is closer to the middle of the RW.

On the other hand, the behavior of the restraint RWs under seismic loads is a principal design engineering issue. This issue is treated using the pseudostatic methods, especially when the acceleration is higher than 0.5 g [31–35]. Nevertheless, various solutions can be adopted to estimate the LST from static and/or dynamic loads; selected solutions are illustrated in Table 2.

The mode of RWs movement in the case of non-restraint conditions is the freely rotating, where they are laterally displaced at their top. These freestanding RWs are like the cantilever RWs. For this mode, the distribution of LST is affected, and the soil-wedge concept is to be activated, and the classic theories of earth pressure can be applied, Rankine and Coulomb theories [36].

The same statement has been proven for the RWs in conditions of low levels of horizontal acceleration under dynamic loadings, where the simplified and Mononobe – Okabe approaches can be used [37]. According to what is mentioned, there are differences in the structural behavior of the non-restrained and the restrained RWs. While the first stands free and translates and rotates, the last cannot translate; instead, it can bend. Nevertheless, the RWs may exhibit partial yielding (partially restrained RWs). A good example of the mentioned case may be noted for the forward movement in the flexible abutments resulting from LST. Under dynamic loads, the behavior of the non-yielding RWs may be impacted by their base rigidity. It was demonstrated that the dynamic LST exerted on restrained rigid-based RWs is 15% to 17% less than that for RWs on a non-rigid base. According to what is mentioned, there are differences in the structural behavior of the non-restrained and the restrained RWs. While the first stands free and translates and rotates, the last cannot translate; instead, it can bend. Nevertheless, the RWs may exhibit partial yielding (partially restrained RWs). A good example of the mentioned case may be noted for the forward movement in the flexible abutments resulting from LST. Under dynamic loads, the behavior of the non-yielding RWs may be impacted by their base rigidity. It was demonstrated that the dynamic LST exerted on restrained rigid-based RWs is 15% to 17% less than that for RWs on a non-rigid base [30].

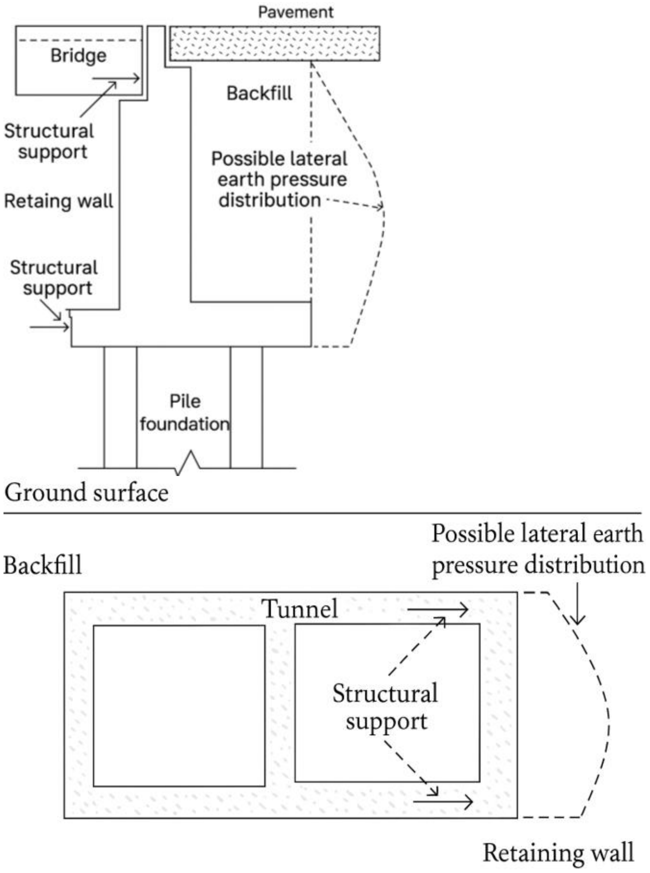

Figure 4. Non-yielding RWs [31].

The yielding of RWs may vary with construction stages. In the early stage, RWs undergo several amounts of yielding before they reach complete non-yielding at the final stage. An example from practice illustrates this case is the case of tie-back RWs. These walls behave as cantilever before the construction of the tie-back. To avoid confusion in such a case, two design stages are to be considered. At the beginning, for a height less than the level of the anchor, the RW is designed with a lesser safety factor, as a yielding wall. Then the design is completed, considering a full non-yielding RW with a fully mobilized anchor [35, 38–42].

RETAINING WALLS EQUILIBRIUM MECHANISMS

RWs get their stability either externally or internally. The equilibrium mechanism in externally stabilized groups comes from an external structure like the group of prefabricated modular RWs (as in gabion, crib, and bin RWs), rigid-semigravity RWs made from concrete, strutted RWs using the ground anchor, or the deadman, the group of non-gravity RWs (like sheet piles and drilled-shafts, soldier-piles and lagging RWs). Meanwhile, the internally stabilized group is different in its behavior; it obtains its stability and resistance to LST by inclusion reinforcement into the mass of soil lying within the area of potential failure and beyond it to a relevant distance. Reinforced-backfill RWs or mechanically stabilized walls (MSWs) with precast facing and a segmental, reinforced-soil slope, geogrid MSW, geotextile MSW, welded wire facing MSW, and soil-nailed RWs are examples of this group Table 2.

The construction method of each group divides it into two main groups. The RWs are either constructed by the cut method, or the fill method. In the group of cut method, the soil is cut or removed by drilling, then the RW is constructed. While in the fill method, the retaining structures are constructed, then backfilled with suitable soil [46–49].

Table 2. Selected solutions are utilized for non-yielding RWs seismic design.

Equation	**Remarks and References**
$\Delta P_E = F\,k_H\,\gamma\,H^2$ Where (ΔP_E) represent the LST under seismic load, (γ) is the unit weight of backfill, (k_H) is the horizontal coefficient under seismic load, (H) is the RW height, and (F) is about one according to [43]	This equation for rigid RWs is constructed on a rigid-base. The resultant force located at 0.13 H above RW middle (i.e., 0.63 H above the base of RW) [43–44].
$Q(t) = \frac{2G}{1-\mu}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{16\,H\,f_{mn}(t)}{\pi^2 L\,(2n-1)^2}$ Where Q(t) is the total dynamic thrust, G and μ are the shear modulus and Poisson's ratio, respectively, H and L are the soil layer height and length, respectively.	This equation is utilized for rigid RW. For harmonic base acceleration $f_{mn(t)}$ is defined as follows: $f_{mn}(t) = \frac{A_{max}}{(\omega_{mn}^2 - \omega^2) + 2i\lambda\omega_{mn}\omega}\,e^{i\omega t}$ Where A_{max} represents the peak horizontal acceleration, ω_{mn} the wall–soil system's angular natural frequency, λ is the modal damping ratio, ω is the excitation angular frequency [33]
$P_{OE} = 0.5\,K_{OE}\,\gamma\,H^2$ Where (P_{OE}) represents the total force (from soil) exerted on RW, (K_{OE}) is the soil pressure coefficient (rigid RW), (H) is the RW's height, and (γ) soil unit weight.	This formula is used for the rigid RW (with sloped backfill), the factor K_{OE} is applied for soil pressure for both seismic and static, according to [45], K_{OE} depends on the ground motions.
$\Delta P_{OE} = 0.3\,PGA\,\gamma\,H^2$ Where ΔP_{OE} is the increment of total seismic LST.	Yi F. (2011) [30] mentioned that the formula utilizes for restrained RW, where PGA is the peak ground acceleration.

The behavior of any retaining wall is impacted by the mechanism the wall uses to keep its equilibrium condition, prevent lateral movements, and balance the LST's moment. Some walls depend on the combined effect of their mass, base width, and the stiffness of the base-ground. This group is termed as a gravity RWs. They are the RWs of large dimensions, where their stable state is reached by equilibrating the applied stresses within the acceptable limits. Also, the part of the filling soil placed on the base of these RWs participated in the stability mechanism. These walls, however, are expensive due to their huge dimensions and space requirements [9, 18, 50, 51].

On the other hand, the stems and bases of the RWs play a main role in resisting LST and providing structural stability. The dead weight of the backfill soil on the heel side of the base contributes to the resistance forces, thus increasing the sliding and overturning stability [3, 52–54]. It is crucial to give the design the gravity and concrete cantilever RWs more consideration for static loads. This does not guarantee the static stability only but also affects seismic stability, as proven in literature. Scholars stated that well-designed RWs for static thrust are well-performed for both dynamic and static conditions. For PGA values less than or equal to 0.3 and 0.4 g, and moderate severity shaking, these walls showed good performance with some permanent displacement. Nevertheless, designing these RWs with inflated safety factors for static conditions produces more stability and prevents permanent movements, but at the expense of the economic side. In place of this, little movement is to be allowed for the RW, which is designed for static loads and in proportional dimensions [32, 55–57]. It is worth noting here that when more than one dynamic load acts simultaneously on a gravity RW, walls with greater self-weight are desired to achieve overall stability. This, however, has its drawbacks from a design perspective. Of course, greater lateral stability against some dynamic loads can be attained with a larger mass. Unfortunately, this may negatively impact stability due to the increased inertial forces of the wall resulting from the earthquake load [3].

The inclined RWs guarantee their stability by leaning the RWs upon the backfilling side. These walls are called leaning RWs (LRWs) (Figure 5). Although they constitute an important part of earth-retaining systems, their stability under seismic loads is poor. In some situations, LRWs can collapse by overturning, as reported in studies of inclined unreinforced concrete walls with narrow foundations. This collapse is attributed to the steep inclination of such walls, which can result in the base of the wall uplifting, thus reducing its stability [58–61].

The structural stability of other types of RWs by reinforcing the soils behind. The interaction between the soil and the mesh or strips included inside the soil, the system produces lateral support to the LST. The mechanically stabilized RWs are an example of such systems. This group of RWs must be carefully designed to ensure stability for internal and external cases. Selecting a proper safety factor is crucial to ensure the stability of mechanically stabilized RWs. This is important for long-term efficiency in reducing the effect of time-related stresses, creep, and temperature. Furthermore, when designing mechanically stabilized RWs reinforced with geogrid, an additional safety factor must be considered, considering factors such as environmental effects, biological damage, joint efficiency, construction method, and backfill soil effect. The backfill characteristics are important in such walls, and different kinds of geomaterials are to be used like Aeolian soil, dune sand, industrial and byproduct wastes [62–64].

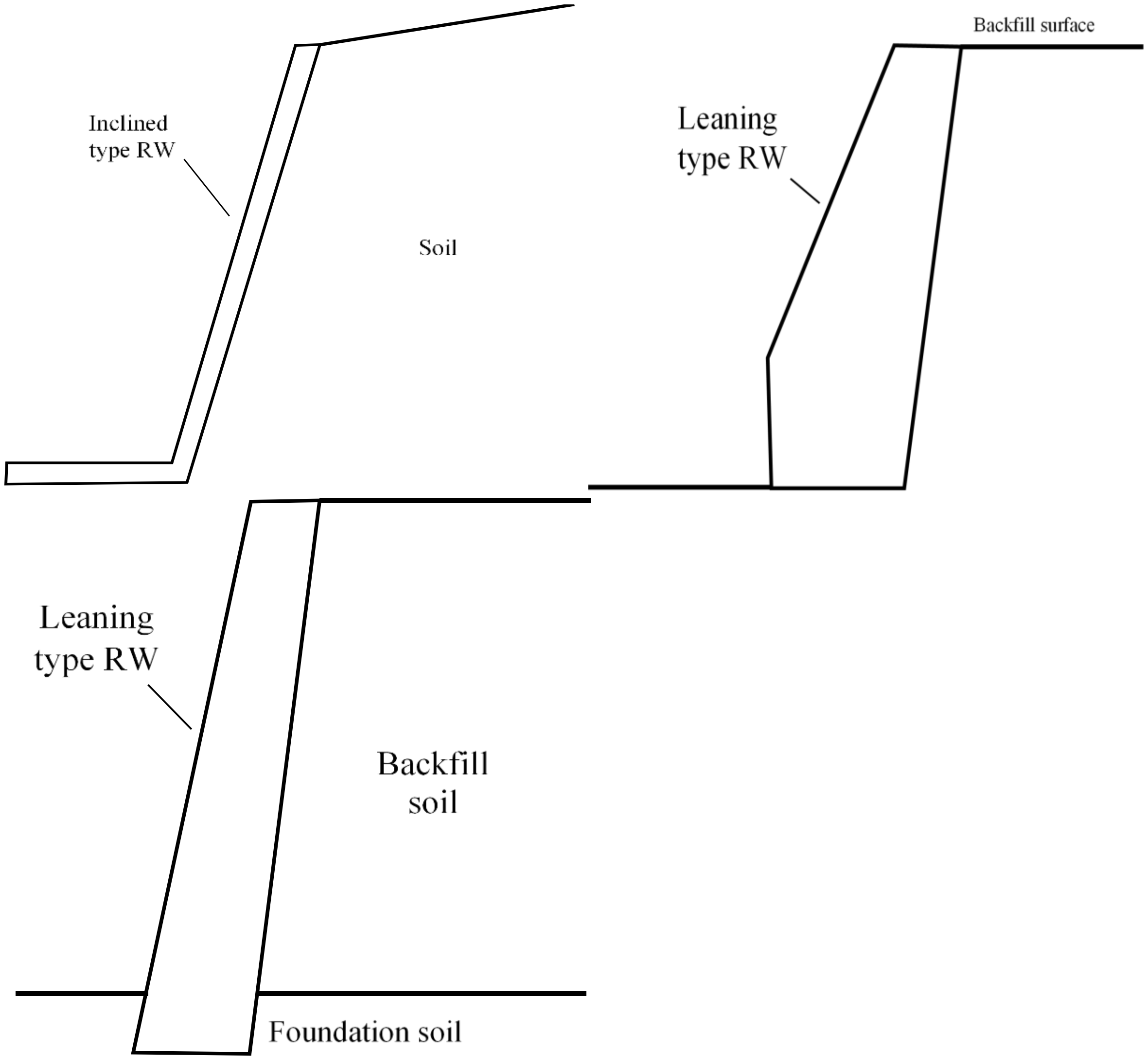

Figure 5. Leaning RWs [65, 66].

Some RWs derived their stability from the interaction with the soil ahead of them and behind them, and the produced passive resistance. They are embedded in the soil to a certain depth, this is the embedment depth, and are baseless structures, called pile-wall systems. An example of them is sheet-piles, soldier-piles, secant-piles, contiguous-piles, and diaphragm-walls. These structures behave as cantilever or anchored RWs. The interaction between the anchors and the surrounding soil (soil of the stable zone) outside the failure wedge provides additional resistance, which positively affects the structural behavior and the stability of RWs. This is obtained by single or multiple anchors, which pull the RW to resist the LST. Examples of anchored pile-wall include in-place piles (e.g., bored and diaphragm piles), and sheet piles [9, 25]. However, two safety factors are to be used in the pile-walls stability analysis. The first is for the embedment depth, where the depth is multiplied by (1.2 to 1.4) to raise its value. The second factor is lowering, from (1.5) to (2.0), utilized for the parameters of embedment depth calculation, (soil cohesion, and passive coefficient) [52].

CONCLUSIONS

The factors that impact structural behavior and yielding of RWs are critical to be considered in design processes. The mechanisms to keep the lateral thrust of RWs within acceptable limits, behavior to support different geomaterials, restraining (yielding), and equilibrium factors are among them.

The LST (magnitude and shape) from static and seismic loads is found to be affected by the RW’s movement mode. RW’s design is influenced by constraint conditions. RWs show different responses with their “yielding” state, clearly different to be noted between “yielding” and “non-yielding” types. As the yielding RWs stand free, they can translate or rotate; meanwhile, the “non-yielding” ones cannot, but they can bend.

Anchor RWs are to serve stability underloading. Using bulky gravity RWs also satisfied the stability condition. Although greater lateral stability (against certain dynamic loads) can be attained by using heavier RWs, a negative effect on stability can occur by increasing the inertial forces of the wall due to earthquake loading. However, a well-designed RW for static loading performs well under seismic loads with (PGA < (0.3–0.4) g) even though the seismic conditions are not considered. Nevertheless, design considerations are necessary to avert the instability of leaning RWs under earthquake shaking. Considerations, also, the case of reinforced RWs to minimize the impact of biological damage and environmental factors on the designed structural stability.

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