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Dynamic behavior of gravity segmental retaining walls

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ABSTRACT

This work aims to highlight gravity segmental retaining walls with their varied advantages. The paper investigates the dynamic behavior analysis of segmental retaining walls. The stability analysis is conducted on the basis of a pseudo-static Mononobe-Okabe theory that provides safety factors against sliding and overturning failure. The results demonstrate that the crucial safety factor of internal stability is the safety factor against overturning. Moreover, the positive wall inclination angle contributes to an improvement in the stability of the segmental retaining walls and the effect of the vertical seismic coefficient on the stability can be disregarding. Finally, a new equation is proposed for the elementary design of the segmental retaining walls.

KEYWORDS

gravity segmental retaining walls, dynamic behavior, stability analysis, pseudo-static approach, Mononobe–Okabe theory

1. INTRODUCTION

Segmental Retaining Walls (SRWs) are gravity structures that depend on self-weight to withstand destabilizing forces caused by retained soil and surcharge loads. SRW systems are built utilizing mortarless concrete block units piled together to create a barrier, which can withstand the backfill soils as it is shown in Fig. 1. This system can be enhanced by inserting many layers of geosynthetic reinforcement into the backfill soil and between the concrete units. These types of retaining walls are characterized by their rapid and easy implementation, environmentally friendly nature, and flexible performance, a drainage face of mortarless units to decrease hydrostatic pressure, as well as the aesthetic and economic considerations and the construction of intricate architectural designs or tight curves designs or tight curves [1].

There are various studies on geosynthetic-reinforced segmental retaining walls in the literature. Helwany et al. [2], Koerner et al. [3] presented the results of their investigation on these retaining walls under seismic loading. The researchers investigated the behavior of these retaining walls as well as the failure mechanism since these structures are considered flexible and allow more displacement in comparison with conventional retaining walls. Over the past two decades, increasingly more numerical analysis has been used to investigate this type of SRW (Liu et al. [4], Guler et al. [5], Ren et al. [6]). For more complicated issues in geotechnical engineering, numerical analysis is deemed to be appealing [7, 8] as with terraced walls, which are considered a challenge in the design domain of the segmental retaining walls.

The literature on gravity SRWs is substantially more limited. This type of retaining wall is utilized for modest heights. The heavier masonry units can be used for larger heights or in cases where it is challenging to employ geosynthetic layers. Using geosynthetic layers necessitates a space in the behind wall for the placement of the geosynthetic layers that is roughly 70% of the wall height or more [9]. Mazni [10] performed two models of SRW in the

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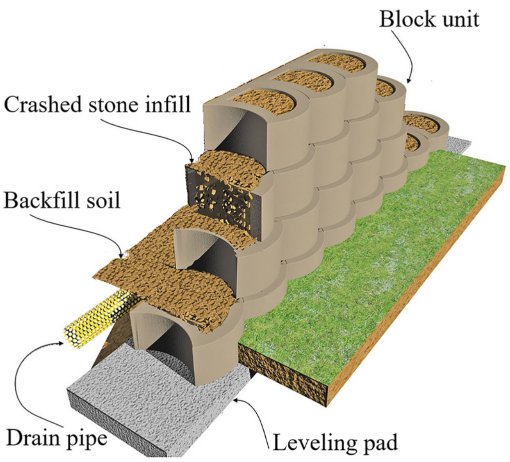

Fig. 1. Segmental retaining wall
(*Source*: basis on www.terraforce.com)

laboratory to study the patterns of slope failures, the findings showing different failure surfaces in comparison to the Rankine theory. Latha and Manju [11] conducted numerous laboratory tests on the geocell retaining walls using the shaking table. The researchers found that the increase of the shaking table frequency increases the horizontal displacements of the retaining walls, as well as the acceleration contributing to the increase of the geocell retaining wall deformation. Toprak et al. [12] proposed utilizing gabions in retaining walls due to their high drainage efficacy. Mazni et al. [13] conducted a new model of SRW to study further the failure mechanism of this type of retaining wall.

Despite the significance of SRWs, particularly in locations where it is problematic to apply geosynthetic reinforcements, the analysis studies were quite restricted and focused on the failure mechanisms. Therefore, the main objective of this work is to revive SRWs and demonstrate their numerous features.

This paper aims to evaluate the stability of SRWs under dynamic loads (earthquakes) and highlight the characteristic of this type of retaining wall in comparison with the conventional retaining walls. Finally, an equation is proposed for the elementary design of SRWs. The internal stability of the segmental retaining walls is the only aspect of this investigation. Design Manual for Segmental Retaining Walls [1] is adopted in this study.

2. MONONOBE–OKABE EARTH PRESSURE THEORY

The pseudo-static Mononobe-Okabe (M–O) theory is employed to determine the dynamic active earth forces applied on the back surface of the SRW that is tilted towards the backfill soil at an angle ω. This is called the wall inclination angle. If this angle faces in a clockwise direction, it is regarded as positive. The backfill soil is tilted from the horizon by the angle β, which is called the backslope angle. Horizontal and vertical seismic coefficients K_h and K_v are specified as fractions of the acceleration of gravity g. For more safety in the design, the direction of the horizontal seismic force is consistent with that of failure as illustrated in Fig. 2. On the other hand, the vertical seismic force acts downward and that corresponds with the positive value of the vertical seismic coefficient. The terms W_w and W represent the weight of the retaining wall and the active soil wedge operating behind the wall, respectively.

The total dynamic active earth force is given as follows [1]:

$$P_{AE} = 0.5 \cdot (1 + K_v) \cdot K_{AE} \cdot H^2 \cdot \gamma, \tag{1}$$

where H (m) is the wall's height and γ (kN/m^3) is the soil's unit weight, K_{AE} is the dynamic earth pressure coefficient, calculated using the formulas below:

$$K_{AE} = \frac{\cos^2(\varnothing + \omega - \theta)}{\cos(\theta) \cdot \cos^2(\omega) \cdot \cos(\delta - \omega + \theta)\left[1 + \sqrt{\frac{\sin(\varnothing+\delta)\cdot\sin(\varnothing-\beta-\theta)}{\cos(\delta-\omega+\theta)\cdot\cos(\omega+\beta)}}\right]^2}, \tag{2}$$

where $\varnothing$ is the peak internal angle of the backfill soil; δ is the mobilized interface friction angle at the unit back, assumed to be equal to $2 \cdot \varnothing / 3$; and θ is the seismic inertia angle is determined as follow:

$$\theta = \tan^{-1}(K_h / (1 \pm K_v)), \tag{3}$$

where K_v is presumed to equal zero in an earthquake, since a simultaneous occurrence of the vertical and horizontal peak acceleration is unlikely. K_h is determined utilizing the specified horizontal peak ground acceleration A which is expressed as a fraction of the gravitational constant g; American Association of State Highway and Transportation Officials (AASHTO) provides the A values [14], and the permitted deflection of the SRW is d. The permitted deflection, d is the maximum lateral displacement that a retaining wall can tolerate during an earthquake. Generally, the typical value is roughly 76 mm. The horizontal seismic coefficient is calculated as follow [14]:

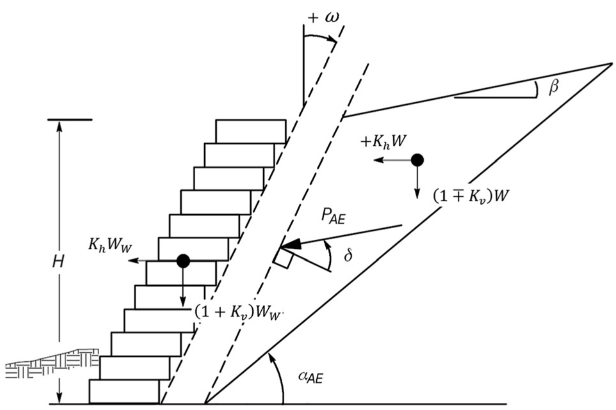

Fig. 2. Geometry and forces in M–O theory
(*Source*: on the basis of [1])

$$\text{If } d = 0.0 \text{ mm}, K_h = (1.45 - A) \cdot A, \tag{4}$$

$$\text{If } d > 0.0 \text{ mm}, K_h = 0.74 \cdot A \cdot (0.0254 \cdot A/d)^{0.25}. \tag{5}$$

Two fundamental issues should be considered in the design: $\theta \leq \varnothing - \beta$ and $k_h \leq (1 \pm k_v) \cdot \tan(\varnothing - \beta)$.

The distribution of the total seismic pressure exerted on the SRW is depicted in Fig. 3. This distribution is adopted in the internal stability analyses of this type of retaining wall.

According to the AASHTO/FHWA (Federal Highway Administration) recommendations, the total dynamic active earth force consists of the active earth pressure force P_A and the increment of the dynamic earth force ΔP_{Dyn} [1]:

$$P_{AE} = P_A + \Delta P_{Dyn}, \tag{6}$$

$$(1 + K_v) \cdot K_{AE} = K_A + \Delta K_{Dyn}, \tag{7}$$

where K_A is the active earth pressure coefficient and ΔK_{Dyn} is the dynamic increment active earth pressured coefficient (for more details, see [1]). According to Fig. 3, the application point of P_{AE} varies depending on ΔK_{Dyn} and ranges between 0.33 and 0.67 H, where H is the retaining wall height.

The internal stability at each interface between the block units is verified by calculating the Safety Factors against overturning (FS_O) and sliding (FS_s), according to the following formulas taking into account the distribution of earth pressure explained above. The details of these well-known formulas can be found in [1]:

$$FS_O = \frac{M_{r,i}}{M_{o,i}} \geq FS_{o-\min} = 1.1, \tag{8}$$

$$FS_s = \frac{R_i \cdot f}{P_i} \geq FS_{s-\min} = 1.1, \tag{9}$$

where $M_{r,i}$ is the resisting moment and $M_{o,i}$ is the driving moment, R_i are resisting forces and P_i are the driving forces, f is the friction coefficient.

3. RESULTS AND DISCUSSION

In this section, the internal sliding and overturning failures of the units along the wall height are investigated based on M−O theory.

A segmental retaining wall is constructed to sustain the soil behind it. The wall height, H is 7.0 m and the used unit width, b and height, h are 1.2 and 0.5 m, respectively. The unit weight of the block units γ_b is 22kN/m^3 and the friction angle between the wall units is 40°. The surcharge load, q is 10kN/m^2. The properties of the backfill soil and the foundation soil and the seismic parameters are listed in Table 1.

For the external and internal stability, the SRW software was designed in an Excel work sheet. This program is used to conduct the parametric analysis and derive an equation, which can be used in the elementary design of SRWs based on M−O theory.

Table 2 presents the summary of the parametric study in this work.

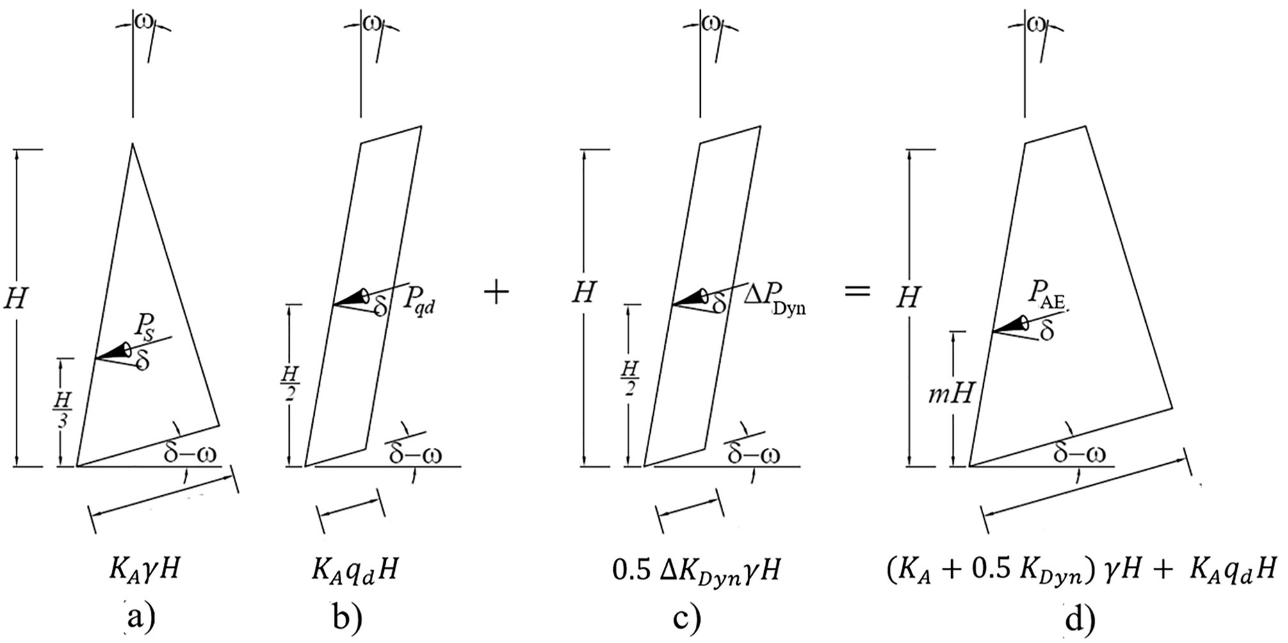

Fig. 3. Distribution of earth pressure as a result of soil self-weight; a) contribution of soil; b) contribution of dead load; c) dynamic increment; d) distribution of total dynamic pressure
(*Source*: on the basis of [1])

Table 1. The properties of backfill and foundation soils and the seismic parameters

Backfill soil		
$\varnothing = 35°$	$c = 0$ (kN/m^2)	$\gamma = 19$ (kN/m^3)
Foundation soil		
$\varnothing = 30°$	$c = 5$ (kN/m^2)	$\gamma = 19$ (kN/m^3)
Seismic parameters		
$A = 0.3$	$d = 50$ (mm)	$K_h = 0.139$
$K_v = 0$		

3.1. Crucial safety factor

An extensive analysis was conducted according to Table 2 to determine the critical safety factor (safety factor against sliding or overturning) in all interfaces between the SRW units along the wall height. The results demonstrated that the safety factor against overturning is the crucial regarding the internal stability of this type of retaining wall.

Figure 4 displays the safety factors against sliding (dashed curves) and overturning (solid curves) for two scenarios, $\omega = 0°$ (left) and $\omega = 20°$ (right). The crucial safety factor that should be considered in the design is the safety factor against overturning in the lower interface.

3.2. Influence of angles (ω, β)

The angle ω influences positively the FS_O. As ω increases, the magnitude of FS_O increases, as it can be seen in Fig. 5. For the given values of ω, increasing the slope angle of the backfill soil, β reduces FS_O; as the value of ω rises, so does the negative influence of β on the FS_O.

Table 2. Parametric study program

ω (°)	0, 5, 10, 15, 20
β (°)	0, 5, 10, 15, 20
b/H (–)	0.16, 0.18, 0.22, 0.27, 0.34, 0.48, 0.8
A (–)	0, 0.05, 0.25, 0.45, 0.65, 0.85
K_v (–)	(−0.66, 0, 0.66) K_h

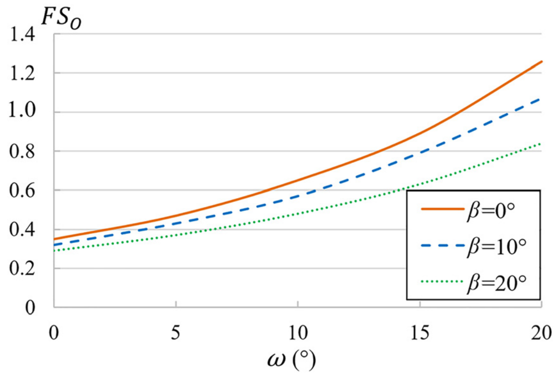

Fig. 5. Influence of ω, β on the crucial safety factors

3.3. Influence of coefficients K_h, K_v

Figure 6 depicts the common effect of K_h and K_v on FS_O for two values of $\omega = 0$, 10. The largest values of FS_O obtained for K_h are less than approximately 0.2 and $K_v = -0.66 \cdot K_h$. Nevertheless, the value of FS_O computed using $K_v = \mp 0.66 \cdot K_h$ is only 4% smaller and 4% larger than the amount obtained using $K_v = 0$ for K_h less than 0.2, respectively. As a result, the presumption that $K_v = 0$ is typically

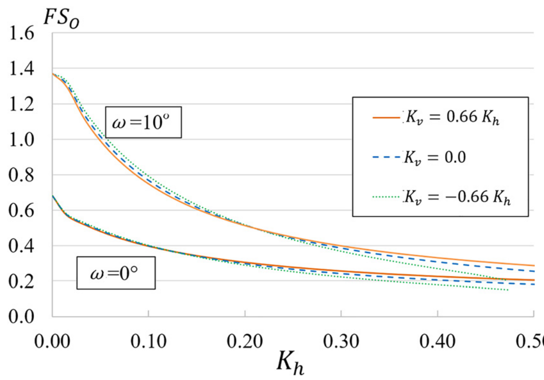

Fig. 6. Influence of K_h, K_v on the crucial safety factors for $\beta = 0$

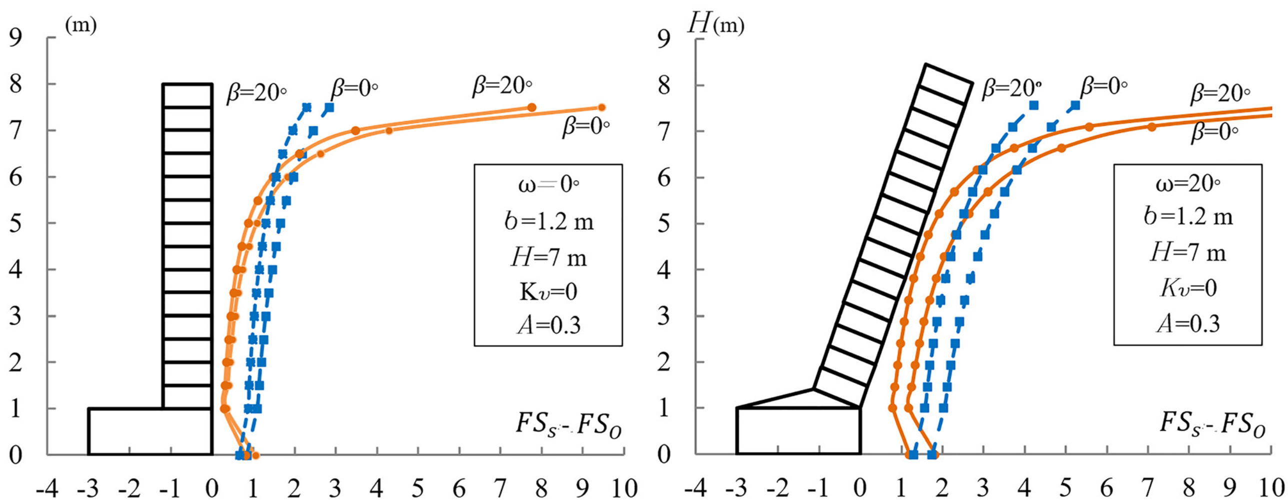

Fig. 4. Safety factors against sliding and overturning, ω=0 (left) and ω=20 (right)

appropriate throughout a large range of horizontal seismic coefficient values.

3.4. Comparison of SRWs and conventional gravity retaining walls

As it was mentioned earlier, ω is regarded as positive if it rotates in a clockwise direction. SRWs are considered flexible as compared to the conventional gravity walls and this is one of the SRW features. In this comparison, the lateral displacement and unit weight of the conventional walls are assumed to be 15 mm and 24kN/m^3, respectively. Figure 7 shows the effect of K_h and ω on FS_O of the SRWs and the conventional retaining walls. The findings reveal that the positive values of ω increases FS_O to values higher than those of the conventional gravity retaining walls.

3.5. Equation of elementary design of SRWs

The proposed Eq. (10) is the result of an extensive parametric analysis depending on the SRW software run using an Excel work-sheet,

$$\frac{b}{H} = \frac{\left(F_1 \cdot \omega + F_2 \cdot \beta^2 + F_3 \cdot \beta + F_4\right) \cdot H}{D_1 \cdot \omega + D_2 + H}, \qquad (10)$$

where $F_1 = 2.5 \cdot 10^{-3} \cdot A^2 - 8 \cdot 10^{-3} \cdot A - 8 \cdot 10^{-3}$; $F_2 = 9 \cdot 10^{-3} \cdot A^2 - 1 \cdot 10^{-4} \cdot A + 1 \cdot 10^{-5}$; $F_3 = -1 \cdot 10^{-2} \cdot A^2 - 1.8 \cdot 10^{-3} \cdot A + 1.5 \cdot 10^{-3}$; $F_4 = 0.4 \cdot A^2 + 0.42 \cdot A + 0.25$; $D_1 = -2.5 \cdot 10^{-3} \cdot A^2 + 4.6 \cdot 10^{-3} \cdot A - 8.1 \cdot 10^{-3}$; $D_2 = -0.125 \cdot A^2 + 0.405 \cdot A - 0.38$.

The first step involves collecting 2,500 values of the dependent variable b/H for different independent variables (ω, β, H, A). The second step is choosing the ratio b/H corresponding to FS_O=1.1, which represents the optimal ratio. This step is followed by statistical analysis of data based on the data structure tree concept in order to derive this equation, which can then be used in the elementary design of SRWs. Curve Expert software is employed in order determine the correlations between dependent and independent variables. The presumed independent variables are listed in Table 3.

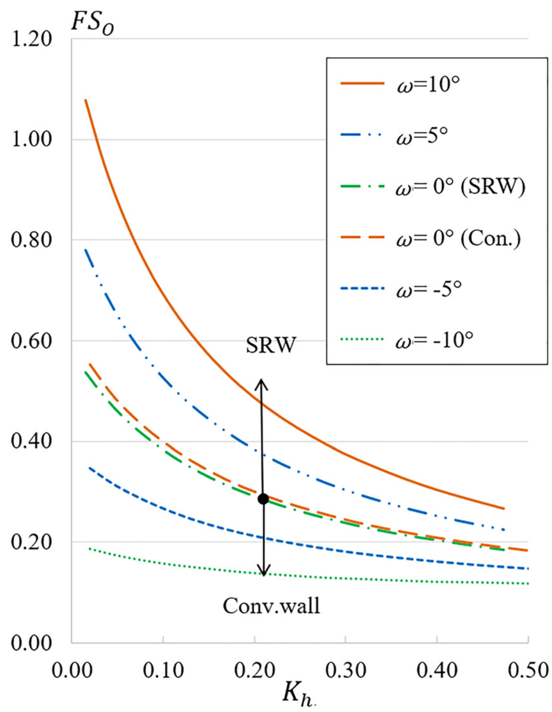

Fig. 7. Comparison of SRWs and conventional gravity retaining walls for β = 0

Table 3. Presumed values of the independent variables

ω (°)	0, 5, 10, 15, 20	H (m)	3, 5, 7, 9
β (°)	0, 5, 10, 15, 20	A (−)	0.1, 0.2, 0.3, 0.4

Table 4. Comparison between the results of the proposed equation and M–O theory

H (m)	b (m)	FS_O (equ.)	FS_O (M–O)	FS_s (M–O)
2	0.52	1.10	1.16	2.12
3	0.71	1.10	1.15	2.19
4	0.91	1.10	1.16	2.25
5	1.11	1.10	1.17	2.28
6	1.31	1.10	1.18	2.31
7	1.52	1.10	1.19	2.34

With this proposed equation, several fundamental concerns should be considered:

- This equation is derived based on the typical properties of the backfill soil and seismic parameters in Table 1;
- γ_b = 22kN/m^3 and q = 10kN/m^2;
- The values of ω, β must be in degrees;
- This equation can be used under static loading with A = 0.0.

Table 4 shows a comparison between the results of the proposed equation and M–O theory in term of FS_O according to the following data $\omega = 20$, $\beta = 0.0$, $A = 0.3$. FS_s is also listed in Table 4.

4. CONCLUSION

In order to analyze the stability of the segmental retaining walls, a pseudo-static approach based on the Mononobe-Okabe theory was adopted in the work. Based on the outcomes of several parametric analyses presented in the paper, the following can be concluded from the segmental retaining wall analysis:

- Between the safety factors against sliding and overturning in the internal stability, the safety factor against overturning in the lower interface of SRW units is the crucial factor. This should be considered in the design;
- The wall inclination angle, ω contributes to improve the stability of SRWs while the backslope angle, β has a negative influence and this influence increases with higher values of ω;

- The influence of the horizontal seismic coefficient K_h is important and contributes to a dramatic decrease in stability while the influence of the vertical seismic coefficient K_v is slight and can be negligible;
- The positive values of ω in SRWs contributes to an improvement in stability while the influence of this parameter is negative in conventional gravity retaining walls;
- A new equation is derived based on the M−O theory. This equation can assist engineers in the elementary design of SRWs.

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