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Review of Studies on Retaining Wall's Behavior on Dynamic / Seismic Condition

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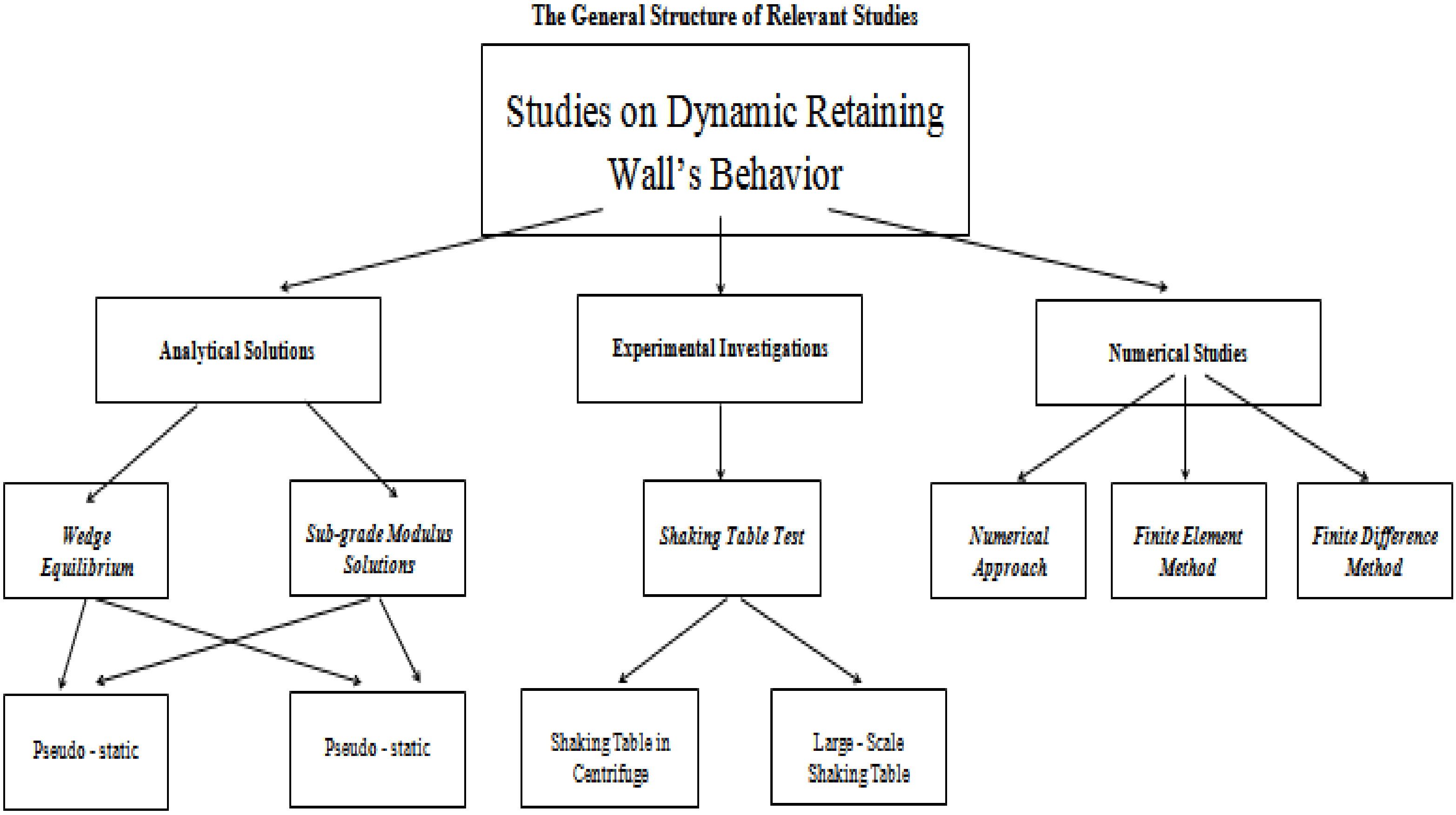
ABSTRACT
Current theories, experimental investigations and numerical findings for retaining walls subject to dynamic excitations are reviewed. Brief features of each method, and experimental and numerical methods are introduced and compared. Tables are listed after each section for a clear and brief view of methods in a categorized manner. Conclusive comments plus current concerns and future expectations of this area are made at last. This review aims at shedding light on the development and concepts of different researches in dynamic retaining wall design and analysis.
Keywords – dynamic, limit equilibrium, retaining wall, review, sub-grade modulus

I. Introduction

Retaining wall systems, consisting mainly of a retaining wall and backfill soil, is a prevalent structure used in our built environment including basement wall, bridge abutments, residential elevations, highway walls and so on. The engineering essence of retaining wall is to keep the retained soil in certain shape and prevent it from falling (stability), or to restrain the deformation of the wall and the backfill to maintain its service function (serviceability). Lateral earth pressure generated by retained backfill on the wall and relevant soil / wall deformations are two main facets of engineering design and analysis of retaining walls. Dynamic/seismic response of such system is one of the major areas due to the influence of dynamic force on the lateral pressure, soil / wall deformation. There are quite a number of analytical solutions, experimental investigations and numerical studies that have been conducted in this area due to different soils, wall structures, dynamic and structural conditions etc. In the meanwhile, it is widely accepted that traditional methods have insufficiencies especially under certain circumstances. As a result, there is a diversity of research to address this issue and try to accurately capture the dynamic response of various retaining systems. However, there is currently no comprehensive and categorized review of current research for dynamic retaining walls. As a result, it is valuable to produce a review of current theoretical solutions and their features; also, significant experimental findings and numerical studies are listed and evaluated. The purpose is to provide peer researchers an overview of the types of research in this area and provides introductive descriptions and critical comments for past studies.

This review work is developed from first author's doctorate research proposal submitted to Curtin University [24]. The general structure and categories of this review are indicated in the next page.



The scope of this review:

1. Studies that proposed fundamental theories or their significant improvements for retaining walls' dynamic response: that is no anchorage or any other enhancing ancillaries, no surcharge, gravity and cantilever type of wall mainly etc.
2. Analytical, experimental or numerical findings that expose new aspects of wall behavior with a significant physical or mechanism basis.

3. Analytical Theories

Currently, there are two main streams of analytical solutions for the dynamic lateral earth pressure of retaining walls: (1) Failure wedge equilibrium theory, which is mainly represented as limit equilibrium analysis (plasticity theory or extension of Coulomb's wedge theory) in which force equilibrium, including dynamic forces (both pseudo-static and pseudo-dynamic) is sought for a failure wedge. (2) Sub-grade modulus (one sub-method of this is elasticity analysis) method, in which the retained soil is considered elements with stiffness modulus such as shear beams or spring systems, so the earth pressure can be gained knowing the displacement of the interface [19]. Only significant theoretical developments are reviewed: many improvements and extensions on those original theories will be neglected or covered very briefly in this section of review.

A. Failure Wedge Equilibrium

1) Review

Mononobe and Okabe [13] (referred to as the MO method in the following text) conducted a series of shaking table tests (using original facilities) following the Kanto earthquake in 1923, and based on the experimental data, they firstly developed a method (MO method) that combines Coulomb's wedge theory with quasi–static inertial force to produce a renewed equilibrium equation, from which the coefficient of active lateral seismic earth pressure can be obtained [13].

It is widely known that some significant assumptions are inherent with the MO method:

1) Dry, cohesionless, isotropic, homogenous and elastic backfill material with a constant internal friction angle and negligible deformation [13].
2) The wall deflects sufficiently to exert full strength along the failure plane [13]. This means no wall rigidity is considered.

What’s more, the MO method is a pseudo-static approach in which the time effect of dynamic force and the dynamic amplification effect are neglected. The MO method as an extension of Coulomb’s wedge theory is a widely used traditional method for solving seismic retaining wall matters. It is widely used as the basic theory for new research and retaining wall design standards, such as Euro code 8 and Australian Standard 4678.

Based on the MO method, Seed and Whiteman [21] investigated the effects of various factors, such as angle of friction, slope of backfill, dry / wet condition, horizontal acceleration, source of load (seismic or blast) and wall friction, on dynamic earth pressure and proposed that dynamic earth pressure can be divided into static part and dynamic part, which then leads into an adaption of the MO method [21]. This simplified method is also widely used as a way to preliminarily solve for dynamic earth pressure issues. On the other hand, rather than one-third above the bottom of the wall from the MO method, Seed and Whiteman [21] proposed a height of 0.6H (H is wall height) above the wall bottom as the location for the resultant force [21].

Deriving from sliding block model, Richards and Elem [18] worked out a serviceability solution (R-E model) with the MO method. The R-E model provided a function for gravity wall displacement. From this, the coefficient of limiting wall acceleration can be solved for [18]. This coefficient is then used as a horizontal acceleration in the MO method to obtain earth pressure. Zarrabi [28] improved this method by taking into account vertical acceleration: this normally renders a slightly lower displacement value than the R-E model. All these methods are summarized by Nadim and Whiteman [14], who also presented a design procedure using displacement-based methods. These methods are categorized as limit equilibrium method since, for all of them, the MO method is used for pressure calculations by knowing the displacement (serviceability requirement) [14] [18] [28].

Since the above mentioned pseudo – static methods neglect the time effect of dynamic excitations and dynamic amplification, Steedman and Zeng [23] investigated the influence of phase on lateral earth pressure, and it was found that dynamic amplification has a significant influence on the coefficient of lateral earth pressure, which is supported by centrifuge tests results [23]. In addition, it can be derived that, for low frequency dynamic excitation, when dynamic amplification is not significant, pseudo – static condition is well satisfied [23]. Also, Steedman and Zeng [23] produced a solution for pseudo-dynamic pressure.

Zeng and Steedman [29] established a method to calculate the rotation of gravity wall subjects to seismic load by modeling the wall as a rotating block [29]. Acceleration needs to reach the threshold to start the rotation, which stops until the angular velocity for rotation is reduced to zero [29]. This method is a pseudo-dynamic one that takes into account time effect of dynamic response [29].

Choudhury and Nimbalkar [5], [6] have established a pseudo - dynamic method for lateral earth pressure and wall displacement in a passive case. In addition to Steedman and Zeng’s [23] [29], they studied and incorporated vertical acceleration, inertia effect between wall and soil and comprehensive relevant factors, but the equations seem lengthy and so hamper practical use. Basha and Babu [4] also did a similar pseudo – dynamic research for the case of failure plane as a curved rupture surface, which is believed to be more realistic [4].

Anderson et al. [3] produced a chart method for the application of the MO method for cohesive soils. The chart method is also limited to cases of non-homogeneous soils and complex back-slope geometry as MO method [3].

Based on the “intermediate soil wedge” theory that relates wall pressure to the strain increment ratio, Zhang et al. [31] developed a new theory to evaluate seismic earth pressures against retaining walls under any condition between passive and active limit states. This method can be viewed as a combination of the failure wedge equilibrium theory and the strain-based pressure theory by Zhang et al [30]. However, the way used to determine a relevant lateral displacement factorusing this solution is difficult in practical use and not interpretative [30] [31].

2) Limitations

The MO method is a limit state method: it only applies when the failure plane is triggered. So it can not be directly used for working state analysis. Although many new solutions have been produced to overcome the inherent assumptions of the MO method, most new solutions seem tedious and so hamper their practical uses. The same goes to the method used to calculate displacements. Also, the location of the resultant force for the MO method is arguable, as well as the stress distribution, especially when the rigidity of the wall exceeds a certain level (this will also be covered in the experimental study section). What’s more, it is widely believed that the wall pressure is directly related to the soil displacement behind the wall. However, many experimental and numerical findings pointed that the MO method and many of its variants do not take into account displacement modes and rigidity of the wall.

B. Sub-grade Modulus Method

In the sub-grade modulus method, the soil-wall interaction is modeled by elements like springs with a stiffness modulus (e.g bulk constant) to relate displacement and generated pressure. These methods are regarded as an alternative way to the MO method for dynamic retaining wall analysis, and were originally used as an elasticity analysis method [19]. Generally, these solutions count soil as elastic, visco-elastic, or plastic material. One significant and simple method under elastic solutions is to represent the interaction between soil and structure in the form of a spring system.

1) Review

To overcome the MO method's inaccuracy for relatively rigid walls, Wood [26] [27] developed a linear elastic theory to estimate the dynamic soil pressures on rigid walls under relatively idealized conditions such as modeling the soil as massless springs [26] [27]. Scott [20] treated the retained soil as shear beams of visco-elastic material that connect to the walls and free at its upper surface [20]. The same as Wood's, only a linear elastic condition with a constant soil stiffness is used in this Winkler - type method. To overcome the drawbacks of Scott's method, Veletsos and Younan [25] utilized semi-infinite, elastically supported horizontal bars, which have mass, to account for the radiational damping effect of the stratum [25]. The same as the previous elasticity methods, springs with constant stiffness are used to model the soil wall interaction [19]. Numerical tool such as MATLAB are needed to solve problems using some sub-grade modulus theories, so some similar studies are included in the numerical section and Table 3 of this review [19].

It is proved that the soil behavior for most geotechnical structures is stress and strain behavior. So understanding soil displacement and stress strain relationship remains an important part for relevant studies. As a result, for the sub-grade modulus method, it is important to shed light on "free-field theories". Free field refers to a field where the dynamic response of the soil is unrestrained, in other words, it is the soil response in a natural field without restriction [19].

The solution for free-field deformation is studied by a couple of researches. Fishman [7] proposed a simplified pseudo-static equation for free field displacement under an active condition with a constant shear modulus (G) and a linearly varying (with depth) shear modulus respectively [7]. Later on, Huang [9] studied plastic deformation in a free field of dry granular soil using the theory of plastic flow. It follows with a solution to calculate the free-field displacement under plastic conditions by incorporating a factor f(kh) into the elastic solution. It is worth mentioning that among the above methods, the soil is elastic – perfectly plastic with Mohr – Coulomb failure criterion and the dynamic force is assumed as pseudo – static [9].

Utilizing the free-field theories developed above, Rowland Richards et al. [19] present a simple kinematic and pseudo – static approach to evaluate the distribution of dynamic earth pressure on retaining structures. Also, both elastic and plastic soil responses are considered. A series of springs are used to model the soil between the free field and the wall [19]. And the spring stiffness is derived from elastic or secant shear modulus in the free field [19]. The wall pressure is obtained by free field stress (using un–mobilized friction angles) and relative deformation between the free–field and the retaining structure [19].

2) Limitations

For the sub-grade modulus method, the formulation of a free- field response is idealized on assumptions such as zero vertical acceleration, pseudo-static etc.: so it does not represent the real free field behavior. And, except in some laboratory studies, only rigid non-deflecting walls are considered by current analytical sub-grade modulus methods [25]. Also, the adoption of a shear modulus is difficult, since G actually varies with confining pressures, strain level and stress history. What's more, the choice of sub-grade modulus is arbitrary; for example, a constant elastic sub-grade modulus is not accurate to represent the true non-linear soil stress strain behavior. The dilemma is, with more factors being taken into account, the solution also becomes more complex and less likely to be used in practice. Alternatively, some elasticity (or sub-grade modulus) theories are to be realized in numerical tools such as MATLAB.

Table 1 listed significant analytical methods that have practical use.

Table 1 List of Analytical Methods for Dynamic Retaining Wall Pressures and Displacement (only Simplified Practical Solutions are listed)

Failure Wedge Equilibrium Method	
Pseudo – Static Pressure/Force	
Mononoke and Okabe [13] :Kae= $\frac{cos^2(\phi-\theta-\beta)}{cos\theta cos^2\beta\cos(\delta+\beta+\theta)[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\theta-i)}{\cos(\delta+\beta+\theta)\cos(i-\beta)}}]^2}$	Most widely used approach. For the walls that have sufficient flexibility and subject to a low acceleration level. Other assumptions need to be met as well. Total pressure at one-third of the wall height above the wall base based on original assumptions.
Seed and Whiteman [21]: Kae = Ka+ $\frac{3}{4}k_h$	Vertical wall and horizontal dry backfill. A simple version for the MO method. Other conditions are similar to the MO method, except a dynamic component acting at 0.6H (H is wall height).
Strain ratio related method for pressures by Zhang, Shamoto et al.'s [31], please refer to relevant papers for approaches.	Lateral pressure at any state can be calculated. Lateral to vertical strain ratio is a crucial parameter, which needs to be determined by site measurement.
A chart method for cohesion soils by Anderson [3], please refer to relevant papers for approaches.	Charts are gained from adaptions of the MO methods for cohesive soils. Conditions for the MO method still apply, except cohesive soil.
Pseudo –Static Displacement	
Richards and Elem [18]:Wall Displacement = $\frac{0.087V^2(\frac{N}{A})^{-4}}{Ag}$	N=ka (horizontal acceleration). This method, combined with pseudo – static approaches with sufficient yield of wall such as the MO method, is able to address serviceability problems for relevant cases.
Pseudo – Dynamic Force/Pressure	
Steedman and Zeng [23]: Pae = $\frac{Q_h\cos(\alpha-\varphi)+Wsin(\alpha-\varphi)}{cos(\delta-\alpha+\varphi)}$	This method takes into account the influence of phase and dynamic amplification factors on lateral earth pressure. Different results to the MO method mainly in terms of pressure distribution.
Choudhury and Nimbalkar's [5] method for pseudo – dynamic earthpressures. For equations please refer to relevant papers.	Vertical acceleration is considered. And taking into account various factors.
Pseudo –Dynamic Displacement	
Zeng and Steedman [23]: rotational acceleration α=[P_{AE}cos(δ+βh+(W/g)$\alpha_g * yc$-W$*$ x_c-P_{AE}sin(δ+βB-h*tanβ)]/[I_c+W/g*r_c^2]	A rotating block method for gravity wall, taking into account the time effect of dynamic load. No inertia force is considered.
Choudhury and Nimbalkar's method [6] for pseud –dynamic displacement. Equations please refer to relevant papers.	Wall soil inertial effect is considered. And taking into account various factors.
Sub-grade Modulus Methods	
Rowland Richards et. al. 's method [19]: $\alpha_{xw}= K_o$z+$C_2\frac{G_{fl}}{H}\sqrt{\frac{z}{H}}[\frac{2k_h\gamma(H^2-\sqrt{Hz^3})}{3G_{fl}}$-$\mu_{w\,max}$ (1-$\frac{z}{H}$)]	Applicable for rigid walls. The value of shear modulus is idealized. The failure criterion can be Mohr–Coulomb, with which the magnitude of pressure is on the conservative side of the MO method.

II. Experimental Findings

The shaking table test and its results are realistic ways of proposing current theories and verify newly proposed theory. The most advanced shaking table tests are the shaking table incorporated with the centrifuge and large-scale shaking table test. Currently, strain gauge, pressure transducers and accelerometers are measuring tools. The walls can be modeled into various conditions such as gravity wall, cantilever wall which are fixed, rigid, flexible etc. respectively.

It is feasible to compare the calculation results, both from previous and current studies, with the results from shaking table tests or the data from previous shaking table test. This review emphasizes experimental studies that have produced useful findings and data on dynamic retaining wall response, and experiments involved in developing or justifying the above-mentioned theories, the MO and Seed and Whiteman mainly, are mostly neglected.

Ortiz Scott and Lee [15] conducted shaking table tests on flexible wall in centrifuge. It is found that the MO method produces reasonable total resultant force [15]. However, the moment the MO method produced is different. In addition, they found that there are post–shaking residual values of all parameters, which are greater than the initial values [15].

Bolton and Steedman [11] carried out a similar centrifuge shaking table test with micro-concrete retaining walls rigidly bolted to the shaking platform. This experimental study justifies the accuracy of the MO method for maximum responses for sufficiently flexible walls. Moreover, it pointed out that the effect of the progressive build-up of permanent deformation over a number of cycles (no later study has been found on this phenomenon) [11].

Sherif et. al [22] experimentally investigated neutral and active static and dynamic stress and the points of resultant by granular soils against rigid retaining walls. They also critically evaluated the displacement needed to develop an active state for both static and dynamic cases and proposed that it increases with wall height and decreases with backfill soil strength [22]. It lays the foundation for further research on dynamic response for various displacements respectively.

Ishibashi and Fang [10] conducted a series of well known shaking table experiments and numerical analysis on a rigid wall with a dry cohesionless backfill. Their research focused on various displacement modes: rotation about the base, rotation about the top, translation and combined modes. The earth pressure distribution, total thrust, and points of application are produced. These results are widely used as reference results for relevant researches. Moreover, the results pointed out the strong dependence of lateral earth pressure on wall displacement modes and influencing factors for soil arching [10].

Fishman et al. [7] conducted laboratory and computational modeling studies on the seismic free field response of sand. They found the benefit of using a flexible end wall for relevant experimental set-ups [7]. Combined with numerical results, the wall pressure, displacement and shear stress were produced for both rigid and flexible walls. One featured finding is that the wall deforms in the same way as the free field (perfectly flexible wall), and the pressure, displacement, and shear stress on the wall are the same as those on the free field [7]. What's more, the methods used for obtaining both small strain and high-strain shear moduli shed lights on relevant experimental researches [7].

The centrifuge shaking table test is conducted by Atik and Sitar [2] to investigate the dynamic pressure and pressure distribution of seismically induced lateral earth pressures on the cantilever wall. In combination with nonlinear finite element analysis, the results firstly prove that triangular pressure distribution, which is assumed by most studies, is reasonable [2]. Another significant finding that the authors proposed is that dynamic earth pressure and inertia force do not act simultaneously and so is maximum earth pressure and maximum moment, which is assumed by the MO method and Seed and Whiteman's solutions [2]. Based on this, suitable suggestions are made to amend the design approach.
Table 2 provides a summary of reviewed shaking table experiments
.

Table. 2 Lists of Reviewed Experimental Findings on Wall Response

Experiment	*Model Wall*	*Type of Soil*	*Experimental output*
Ortiz， Scott and Lee's [15] centrifuge shaking table test	two aluminum plates dip – brazed together (reinforced concrete cantilever)	fine sand with medium density, varied slopes of backfill	plots of moment, shear, pressure, and displacement over the height of the walls as a function of time
Bolton and Steedman's [11] centrifugal shaking table test	reverse t – section retaining wall made of micro-concrete	dry sand backfill with varying density	base moment due to tip load, wall crest deflection with acceleration
Shaking table test OF Sherif et al. [22] (large shaking table – retaining wall assembly)	rigid retaining wall, movable	granular soils	lateral pressure in active state and at rest, the location of force application
Ishibashi and Fang's [10] shaking table test (large shaking table – retaining wall assembly)	rigid movable retaining wall with configurations allow various displacement modes	dense air – dried Ottawa sand	pressure distribution, dynamic resultant force, incremental dynamic thrust, and points of application under various displacement modes
Atik and Sitar's [2] centrifugal shaking table test	cantilever retaining wall	fine, uniform, angular Nevada sand under medium-dense state	dynamic earth pressure and moment along depth and with time of shaking

III. Numerical Studies

Recently, engineering numerical techniques are developing very fast, which renders numerical methods as a crucial tool in engineering research, design, and analysis. Nowadays, numerical analysis usually accompanies experimental findings for geotechnical research. In this review, no holistic history of numerical studies is provided: instead, some significant recent studies using more advanced modeling techniques are selected. The numerical studies that have been used to assist analytical or experimental studies that have been mentioned above are neglected.

Veletsos and Younan [25] did numerical studies on the influence of wall and it's base flexibility on the response of retaining wall subjects to horizontal ground shaking. Both harmonic base motions and an actual earthquake record are investigated. The results show that a fixed based flexible wall triggers significantly higher wall pressure than walls of realistic base and wall flexibilities [25]. Besides, the dynamic amplification factor is also affected by those flexibilities [25].

Al-Homoud and Whitman [1] developed a two dimensional finite element model for THE seismic response of highway bridge abutment. FLEX is the verified code used in this case, and a viscous cap is the constitutive model [1]. Far–field ground motion is modeled by placing shear beams [1]. The results of this numerical study agree well with relevant experimental results and have shown that outward tilting is a dominant mode of response for this case. This also corresponds well with a real case [1].

Psarropoulos et al. [17] utilized the commercial finite–element package ABAQUS to test some analytical solutions (Veletsos and Younan's elasticity method mainly) and the range of applicabilities of these solutions [17]. The soil model is visco-elastic. The results also verify the MO method and the elasticity method for flexible walls [17]. It also investigated the effects of soil inhomogeneity, flexural wall rigidity and translational flexibility of the base of the wall.

Green et al. [8] conducted a series of non–linear finite difference analyses to investigate cantilever walls using FLAC as the code, and an elasto-plastic constitutive model combined with a failure criterion of Mohr-Coulomb is used to model the soil [8]. Emphasise is on calibrating and validating the soil–wall system model. This study justifies the MO method for low acceleration level, but showed discrepancies when acceleration is high, which is due to flexibility of the wall [8]. Also, the study found a different critical load case between soil failure and structural design, which corresponds well to Atik and Sitar's [2] experimental findings mentioned above.

For reference of a detailed numerical review, Pathmanathan [16] produced a more detailed account of some of the numerical studies with useful comments.

A list of critical points of reviewed numerical studies is listed in Table 3.

Table 3: Lists of Configurations for Reviewed Numerical Studies Lists of Configurations for Reviewed Numerical Studies

Experiment	***Model Wall***	***Dynamic Excitation***	***Soil Model***	***Constitutive Modes***	***Soil Wall Interaction***	***Numerical Output***
Veletsos and Younan's [25] numerical study	flexible cantilever wall with various flexibilities, the base is elastically constrained against rotation	static excitation, harmonic base motion, actual earthquake record, respectively	linear, uniform, and visco-elastic stratum with semi-infinite boundary	n/a	complete bonding	displacement of the wall, wall pressure, shear, bending moments
Al-Homoud and Whitman's [1] two-dimensional finite element model using finite element code FLEX	rigid structure to model bridge abutment	different sinusoidal and earthquake acceleration input motions	dry sand by 2D element grid	viscous cap constitutive model	interface elements that interpret bonding, de-bonding, and sliding	wall pressure, wall tilt, dynamic resisting moment, etc.
two – dimensional finite element analysis of Psarropoulos et al. [17]	flexible wall elastically restrained at base, rigid gravity wall	effectively static / dynamic harmonic excitation	visco–elastic material, homogeneous and inhomogeneous respectively	n/a	complete bonding	dynamic earth pressure of varied wall structural and base flexibilities
non – linear expllicit finite difference analyses using FLAC code of Green et al. [8]	concrete wall consists of five segments with constant parameters, and made by elastic beam elements	excitation generation techniques using other software	compacted soil with medium density and without cohesion	elastic-perfectly plastic , plus Mohr-Coulomb failure criterion	interface elements developed to overcome restrictions	wall pressure, permanent relative displacement, etc.

IV. Conclusion and Comments

Current theories, experimental findings and numerical studies for retaining walls subject to dynamic excitation have been briefly listed in a generally chronological order. Numerical analyses are an accurate way to solve relevant problems, while experiments are good but incur big cost to conduct an accurate one. In spite of these, the MO method is still a current main approach for practical use due to its simplicity. But the MO method becomes impractically complex when more factors like the influence of pseudo–dynamic, logarithmic failure plane etc is being considered, not to mention the widely known assumptions that are inherent with the MO method. It is found that the results from the elasticity method are from 2.5 to over 3 times higher than those from widely used the MO approaches [25]. Also, for the method of Rowland et al.'s [19], the obtained pressure is on the conservative side of the MO results [19]. However, although some people states that the MO method is not safe under seismic excitation (a typical example is active failure of bridge abutment under seismic excitation), it seems that there are more researches found from real earthquake records that show walls designed for a static case are already satisfactory [12], so efforts need to be made to make the retaining systems more economic. In this sense, considering the current sub-grade modulus method is even more conservative than limit equilibrium methods, the practical use of sub-grade modulus method can be accompanied with a reduction factor. On the other hand, the sub-grade modulus method tries to interpret real soil behavior and wall response, so the underlying theories and concepts being used are highly valuable for understanding the real physical behavior of dynamic retaining walls.

The assumption of a rigid wall is one reason for high pressure obtained from non–numerical analysis of sub-grade modulus theories. Besides, it is widely suggested that the MO method should be used for low excitation and flexible walls. Both experimental and numerical results have pointed out the strong dependence of earth pressures on wall flexibility, which is in essence a matter of displacement trigged stress variation [22] [25]. However, although soil displacement in a free–field has been studied by some researched mentioned above, there is a paucity of understanding about soil displacement behind the wall or in the near field for dynamic cases. As a result, dynamic soil displacement and stress–strain behavior would be an area of future interests.

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