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RECENT ADVANCES IN SEISMIC DESIGN OF GEOSYNTHETICALLY-LINED WASTE CONTAINMENT FACILITIES

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ABSTRACT

Geosynthetic materials are essential elements of almost all modern landfill barrier systems. Materials such as geomembranes and geosynthetic clay liners are widely used as resistive barrier elements while geotextiles, drainage nets, and geocomposites are widely employed in modern composite barrier systems for both landfill liners and covers. The ability of these geosynthetic elements to maintain their integrity when subject to deformations due to waste settlement and seismic loading is a major uncertainty with respect to the performance of modern landfills. Over past years, advances have been made in understanding of material behavior under cyclic loading, modeling of modern landfill response to strong ground shaking, and interpretation of the analysis results. This paper presents, by reference, results of relevant recent research including advances in evaluation of dynamic material properties of municipal solid waste (MSW) and special wastes, dynamic testing of barrier system interfaces, understanding of decoupled and fully coupled response analysis, and advances in constitutive and numerical modeling relevant to better modeling of seismic response of modern landfills. Based upon the synthesis of this information, it is concluded that the commonly used decoupled approach is reasonably conservative and can be used for seismic design of modern waste containment facilities until fully coupled approach and associated evaluation and modeling of interface parameters evolve to be usable from both the practical and economic points of view.

INTRODUCTION

Modern solid and hazardous waste landfills are lined, and in many cases capped by composite barrier systems. The term composite barrier system refers to a liner or cover system composed of either compacted clay liner (CCL), or Geosynthetic Clay Liner (GCL), overlain by a geomembrane (GM). This type of barrier systems has been mandated for hazardous waste landfill liner and final cover systems in the United States since 1985 (Subtitle C Regulations), and for new construction and lateral expansions of municipal solid waste (MSW) landfills since 1993. The 1993 regulations for MSW landfills, commonly referred to as Subtitle D, imply that MSW landfills with geomembranes in the basal liner system should be capped with a cover system that includes a GM. Composite final cover systems, or caps, that contain GMs are also widely used for remediation at Federally-mandated corrective action sites, including Superfund sites. Subtitle D regulations mandate that landfills in approximately 40% of the continental United States must be designed to resist seismic loading.

While the regulations mandating geosynthetic liner and cover systems typically prescribe that the GM be underlain by a compacted clay liner (CCL), they also usually allow for the use of engineered alternatives to the prescriptive barrier. Under these provisions, GCLs, which are 6 mm-thick layers of sodium bentonite sewn or needle-punched between two geotextiles or glued to a carrier geomembrane, have become established as a preferred alternative to a CCL in the composite barrier. This substitution is particularly advantageous for side-slope liner systems in canyon landfills where steep slopes make construction of a CCL difficult and expensive, if not prohibitive. GCLs also offer the benefits of faster construction, more consistent quality, lower cost if high quality clay is not locally available, increased useable airspace, and reduced environmental impacts during construction.

Other geosynthetic elements routinely used in landfill liner and final cover construction include geotextile filters to protect drainage layers from clogging, geotextile cushions to protect geomembranes from puncture, drainage nets and prefabricated drainage geocomposites. Stacked cylindrical geotextile tubes and bags (geotubes) have also been used for containerized disposal of special wastes, sludges, and contaminated sediments. Figure 1 shows a typical base and side-slope liner system for a canyon landfill in California. The base liner employs a CCL and GM to form a composite liner while two alternative configurations (with GCL and CCL) are shown for the side-slope liner. Base liner systems and composite final cover systems of modern landfills outside California often have configurations similar to Fig 1.

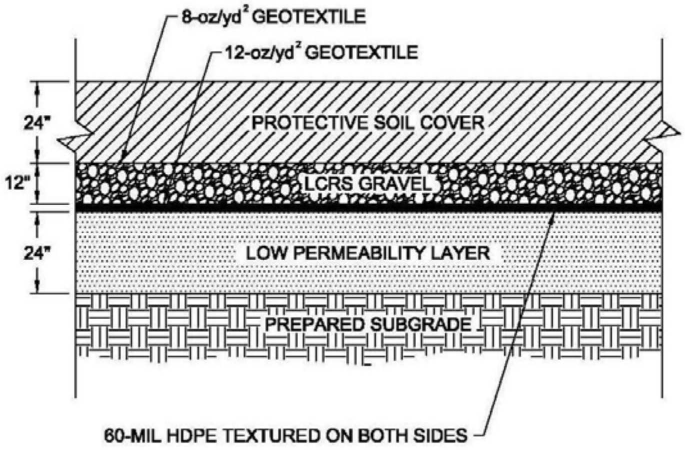

Fig. 1a. Typical composite base liner system of modern landfill.

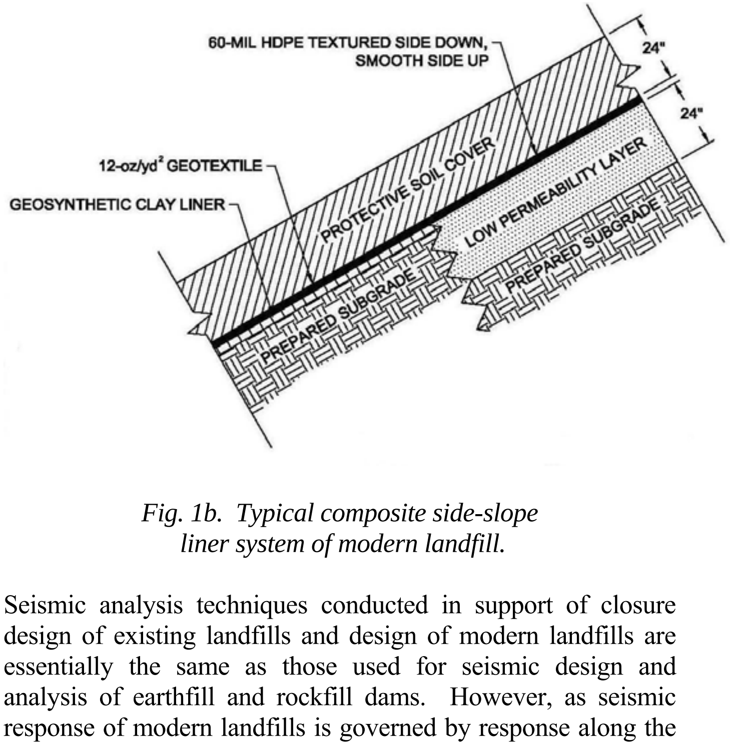

Fig. 1b. Typical composite side-slope liner system of modern landfill.

Seismic analysis techniques conducted in support of closure design of existing landfills and design of modern landfills are essentially the same as those used for seismic design and analysis of earthfill and rockfill dams. However, as seismic response of modern landfills is governed by response along the composite liner interfaces, special considerations are required to evaluate the response. These considerations include evaluation of the material properties of the liner system, modeling of liner system interfaces, evaluation of the material properties of waste, and numerical modeling considerations that are explained in this paper.

DYNAMIC MATERIAL PROPERTIES

General

The material properties required for evaluation of seismic response of modern landfills include the unit weight, shear modulus, internal (material) damping, and Poisson's ratio of waste. The variation of these properties with shear strain amplitude and effective confining pressure is also important. For the decoupled site response – seismic deformation analysis explained below, an extended set of material properties is required. This extended set includes, in addition to the properties listed above, the shear strength parameters of waste and along the composite liner and cover interfaces. Both peak and residual shear strength parameters may be required for evaluation of the stability of the composite liner and cover interfaces.

Fig. 2. MSW landfilling operation at a canyon landfill.

Municipal Solid Waste and Bioreactor Landfills

Most of the waste generated in the United States and abroad is MSW. MSW disposed of in modern landfills is often stripped of paper, glass and other recyclables, is subject to a certain disposal restrictions, and is often compacted during placement in approximately 3-m thick lifts. Typical waste disposal procedures call for placement of at least 150-mm of soil or an approved alternative material over the waste at the end of each day. After placement in a landfill, MSW undergoes significant volumetric compression under self-weight and is subject to decomposition and additional compressibility. This results in a relatively large settlement not only during filling operations but also after landfill closure (e.g., Edil et al. 1990, El Fadel et al. 1999, Park et al. 2002). A MSW landfill will typically settle approximately 15 to 20% of the overall waste thickness after closure, and these settlements are in addition to the significant settlement (due to both self-weight and decomposition) that occurs during waste placement. As the maximum earthquake, i.e., design seismic event with return period of 500 to 2,500 years is likely to occur following landfill closure, many engineers choose to base the seismic design of MSW landfills upon dynamic material properties evaluated by testing "older" (50 to 60 year old) waste.

Several researchers tested samples of "older" MSW for various purposes. Kavazanjian (2006) and Zekkos et al. (2007) provide a recent summary and interpretation of relevant testing programs. Matasovic and Kavazanjian (1998), Matasovic et al. (1998), and Kavazanjian et al. (1999) developed a consistent (i.e., properties developed by in-situ and laboratory testing and back-analysis of response of the same waste to ground shaking) set of dynamic and static (shear strength) material properties suitable for seismic design of MSW landfills. This work included development of 457-mm diameter Cyclic Direct Simple Shear (CyDSS) and Cyclic Direct Shear (CyDS) devices suitable for testing of MSW samples recovered by large-diameter bucket auger drilling. The CyDSS device developed for this work is shown in Figure 3 and is described in greater detail in Matasovic et al. (1998).

Fig. 3. Large-diameter CyDSS apparatus (currently at Arizona State University).

The in-situ testing program coupled with the laboratory testing program conducted using the above shown and described CyDSS and CyDS devices, and supplemented by back analysis of on-site recorded strong motions resulted in a consistent set of MSW properties, including the unit weight, Poisson's ratio, and shear wave velocity profiles for "older" waste. This set of material properties is presented, along with the modulus reduction and damping curves of the same waste, in Matasovic and Kavazanjian (1998). The shear strength envelope of this waste is presented in Kavazanjian et al. (1999).

In the areas of high seismicity, such as the West Coast of the United States, seismic design of modern MSW landfills often includes evaluation of interim stability of lined waste fills. As interim condition of landfill development is not anticipated to last more than few years, material properties of "young" waste may be appropriate for interim seismic design evaluations. Zekkos et al. (2007a) performed over 90 large-scale cyclic triaxial (CTX) tests on 300-mm diameter specimens for three sample groups of solid waste with ages ranging from less than 2 years old to 15 years old collected from a northern California landfill. The generic material properties from this study include unit weight profile, modulus reduction and damping curves (up to approximately 0.8 percent shear strain) and shear strength envelope.

It is not clear if seismic design of MSW landfills based upon generic (both "young" and "older" MSW) material properties is reasonably conservative, and if it is, to what degree. Athanasopoulos-Zekkos et al. (2008) attempted to evaluate how adequate (i.e., conservative) seismic design of MSW landfills based upon published generic material properties is. The basis for the evaluation was one of very few well documented landfill case histories, the OII Landfill, California case history (see, e.g., Augello et al., 1995; Matasovic and Kavazanjian, 1998; Elgamal, 2004) and generic material parameter sets. The results indicated that the use of generic material parameter sets, at this site results (bedrock Peak Horizontal Ground Acceleration, PHGA ≈ 0.1 g), in either reasonable prediction or slight over-prediction of recorded ground motions.

Bioreactor landfills are MSW landfills where significant amount of liquid is injected into waste mass to enhance and speed-up volumetric compression due to decomposition. Shear strength parameters of waste disposed of in bioreactor landfills are discussed in Kavazanjian (2001), Bachus et al. (2004), Gabr et al. (2007), and Reddy et al. (2009). The available data indicate that the primary impact of leachate recirculation and bioreactor technology on the mechanical properties of MSW is an increase in waste unit weight. Kavazanjian (2006) postulated that MSW shear strength is largely unaffected by liquid addition or enhanced degradation when viewed on an effective stress basis while stiffness (i.e., modulus reduction and damping) is impacted only to the extent that stiffness depends upon unit weight.

Kavazanjian et al. (1999) measured relatively large volumetric strains of up to 5% during large-diameter CyDSS testing of MSW recovered from saturated zones of the OII Landfill. These measurements suggest that there is a potential for development of excess porewater pressure due to cyclic loading of saturated waste. The magnitude of this pressure and its impact on landfill stability may require special attention with respect to seismic design of bioreactor landfills in areas of high seismicity.

Special Wastes

The special waste category includes wastes ranging from asbestos, fly ash, and shredded tires to containerized liquid waste and fine grained contaminated sediments and sludges disposed of by means of geotubes Typical containerized liquid waste disposal practice is shown in Figure 4. The disposal (consolidation) of contaminated sediments by means of stacked geotubes is shown in Figure 5.

Fig. 4. Disposal of containerized liquid waste (Matasovic et al., 2006).

The seismic design of geosynthetically-lined special and mixed waste landfills is based, like its MSW counterpart, upon generic material properties. However, limited information on dynamic and shear strength properties of special wastes is available. Matasovic et al. (2006) provided a shear wave velocity profile for design of containerized liquid waste landfills and undrained shear strength of these materials. Zhu et al. (2010) developed generic shear strength parameters and a method for evaluating the stability of a landfill constructed from stacked Geotubes filled with fine-grained sediments.

Fig 5. Sediment disposal using flat geotubes (Zhu et al., 2010).

Poran et al. (1994) measured shear wave velocity in the Town of Babylon, New York, ashfill. Ash disposed of at that site was generated by the Town's waste-to-energy facility. Results from the Poran et al. (1994) measurements are compiled in Figure 6 and are further processed to include a "recommended" curve for seismic design of ashfills. Cappai et al. (1999) report shear strength parameters for incinerated MSW (ash from waste-to-energy facilities) that can be used for design until more data on ashfill shear strength and other properties become available.

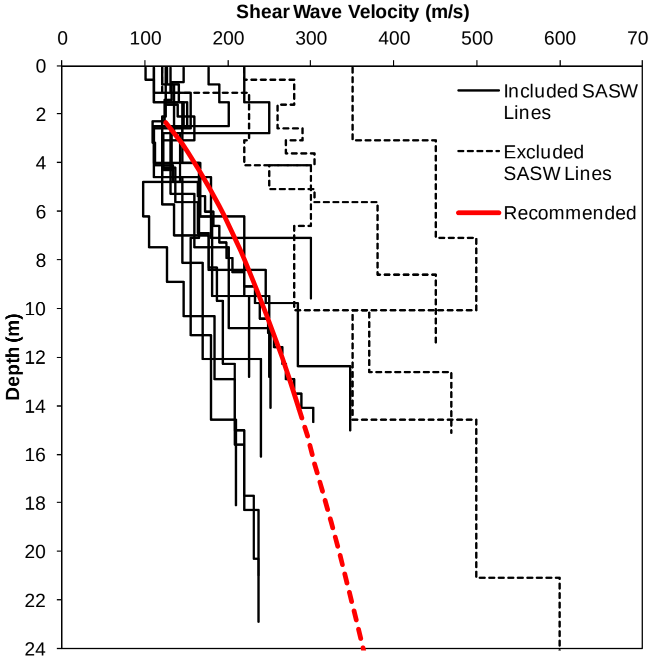

Fig 6. Shear wave velocity measurements in Town of Babylon, New York ashfill and "recommended" curve for seismic design of ashfills.

DYNAMIC IN-PLANE SHEAR STRENGTH

There is ample information on the in-plane (interface and internal) static shear strength of modern composite liner systems (e.g., Mitchell et al. 1990, Stark and Poeppel 1994, Stark et al. 1996, Chiu and Fox 2004). This body of information is constantly expanding as (static) interface direct shear testing is routinely mandated and performed as a part of modern landfill design and construction quality assurance. However, information on dynamic interface and internal shear behavior (e.g., on interface strength under cyclic loading conditions), is sparse. Information vital to dynamic analysis such as rate-dependent effects, cyclic stress ratio versus number of cycles to failure, hysteretic stress-strain relationships, and shear stiffness and damping, is almost non-existent for composite liner interfaces.

In a few cases, composite landfill liner and cover interfaces have been tested under dynamic loading conditions. Most of these studies have been conducted using shaking tables or centrifuges. Representative studies include work by Kavazanjian et al. (1991), Yegian and Lahlaf (1992), De and Zimmie (1998), Yegian et al. (1998), Yegian and Kadakal (1998a and 1998b), and Kim et al. (1995). Most of these tests are shaking table tests, which due to the equipment limitations, are constrained to very low normal stresses (< 50 kPa), dry conditions, and/or small specimens (300 by 300 mm). Furthermore, these studies have generally investigated interfaces between geomembranes, geonets, and geotextiles, and did not include GM-CCL or GM-GCL interfaces, which are the most critical interfaces in many cases. For example, prior to the recent large diameter cyclic shear test results on a needle-punched GCL reported by Nye and Fox (2007) and Fox et al. (2009) (see Figures 7 and 8), the only detailed information available on the dynamic behavior of GCLs was from direct simple shear tests performed on small specimens of an unreinforced GM-supported GCL by Lai et al. (1998).

Fig 7. Large-diameter cyclic direct shear machine used by Nye and Fox (2007).

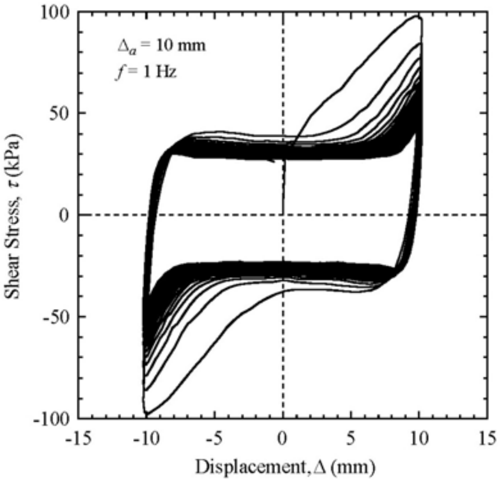

Fig 8. Dynamic internal shear test of GCL results by Nye and Fox (2007).

While the Nye and Fox study is the most informative study on the dynamic behavior of GCLs to date, these tests were all conducted at a normal stress of 141 kPa and thus are of limited use for design of modern lined landfills where design normal stresses may range from 500 to 2,000 kPa. Additional test data are needed on the load-deformation behavior of many other potentially critical landfill liner materials and interfaces during dynamic loading, particularly under moderate and high normal stress conditions.

SIMULATIONS, PHYSICAL MODELING, AND OBSERVATIONS

Simulations of MSW Settlement Impact

Fowmes et al. (2005; 2006) simulated the behavior of a side-slope composite landfill liner system subject to MSW settlement. The simulation was performed by means of the finite difference method as coded in the computer program FLAC™ (www.Itasca.com). The results of Fowmes et al. (2005; 2006) study numerically confirmed what many engineers suspected, but few have observed – that MSW settlement can induce significant tensile strains in geosynthetic components of side-slope composite liner system. The consequences of this finding are twofold: (i) cushion geotextile, with its relatively low axial strength, may lose its integrity and hence leave portions of the primary barrier (GM) unprotected, as illustrated by Dixon and Jones (2005) and reproduced in Figure 9; and (ii) significant axial stress (and strain) in GM may develop. Both of these consequences may be exacerbated by seismic loading. Besides inducing the MSW settlement, seismic loading may induce transient and residual strains in GM, as demonstrated by the centrifuge testing discussed below.

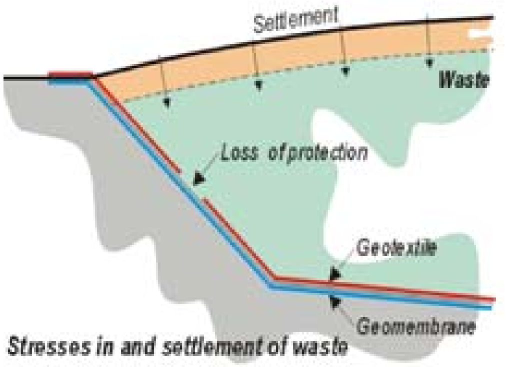

Fig.9. Impact on side-slope liner geomembrane due to static (and seismic) settlement (Dixon and Jones 2005).

Physical Modeling of Landfill Response

To achieve model similitude, "model" waste is required for use in centrifuge simulations of modern landfill response to strong ground shaking. Thusyanthan et al. (2006a; 2006b) developed "model" waste and, by the means of the Cambridge University, United Kingdom, centrifuge and modified Equivalent Shear Beam (ESB) container (shown in Figure 10), conducted a series of static and dynamic tests. The models were of general configuration shown in Figure 11 and included 15-m thick waste fill with relatively steep (1Horizontal: 1Vertical) side-slopes. The later series of tests included a composite liner system placed over landfill base and side-slopes. Partial test results are presented in Figure 11 while test details and a full set of results are presented in Thusyanthan et al., (2006a; 2006b; and 2007).

Fig. 10. Equivalent Shear Beam (ESB) container (Thusyanthan et al., 2007).

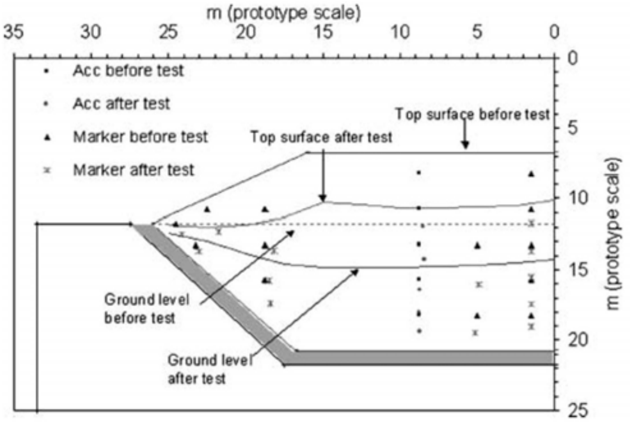

Fig. 11. Post-centrifuge test settlement profile of the landfill model (Thusyanthan et al., 2006b).

The tests were validated by comparing the measured material properties to their counterparts evaluated by testing actual MSW. The interpretation of the initial test results in terms of recorded acceleration and settlement values. Cracking corresponding to approximately 500 mm of prototype displacement at the toe of waste slope was also observed. The observed settlement profile and cracking indicated that notable tension may develop in the landfill side-slope liner. The results of subsequent centrifuge testing with instrumented side-slope liner indicated that significant transient and residual strains in the GM of the side-slope liner can be induced by shaking. For the model base excitation of 0.08 g, during shaking, the relative increase (i.e., compared to the static settlement induced strain) was up to 25%. The residual value was 15%. For model base excitation of 0.2 - 0.3 g, the transient increase was up to 40%, with residual value of up to 25%.

Observations

Interpretation and analysis of observational data on the performance of solid waste landfills during earthquakes is the most reliable source of information on the seismic response of solid waste landfills. The data from several major earthquakes (see, e.g., Matasovic et al. 1995; Augello et al., 1995; Matasovic and Kavazanjian, 1996; Matasovic et al., 1998; Matasovic and Kavazanjian, 2006) indicate that the general performance of landfills during earthquakes is from good to excellent. However, only two landfills lined with geosynthetic liner systems designed in compliance with modern (e.g., EPA Subtitle D) standards have been subjected to strong ground shaking (bedrock PHGA in excess of 0.3 g) in a large magnitude (**M** 6.7) earthquake. The only modern geosynthetically-lined landfill that suffered some limited damage to the containment system (Chiquita Canyon Landfill in greater Los Angeles) was subject to bedrock PHGA of approximately 0.25 g. The observed damage (i.e., tear in 1.5-mm thick, smooth GM) was above the waste and hence did not result in a release of contaminants to the environment).

Implications

Studies by Fowmes et al. (2005; 2006) and Thusyanthan et al., (2006a; 2006b; and 2007) indicate that relatively large MSW settlement may induce relatively large (initial) shear and axial stress in GM and GCL of side-slope composite liner system, and that both stresses (and axial strain) can be exacerbated by strong ground shaking. Both studies are limited, however, to certain waste fill thickness, waste material properties, side-slope liner material properties and geometry as explained above. Furthermore, simulations by Fowmes et al. (2005; 2006) are limited to static loading, while centrifuge modeling by Thusyanthan et al. (2006a; 2006b; and 2007), is limited to bedrock PHGA of approximately 0.3 g. Nevertheless, the results of these studies indicate that, under certain combination of the parameters listed above, and especially in areas of high seismicity, the damage to the composite landfill side-slope liner systems may occur. Given the difficulty of detecting damage in a burred liner system, the National Research Council (NRC, 2007) recognized that possibility as a serious concern and recommended further research of the phenomenon.

METHODS OF ANALYSIS

General

The seismic design of modern geosynthetically-lined and capped waste containment facilities is not bound by a single method of analysis. The conventional, stress-based pseudostatic analysis with the seismic coefficient treated as an empirical constant and applied in a horizontal direction is widely used in areas of low to moderate seismicity. Modern, performance-based analysis, is more frequently used in the areas of high seismicity. However, performance-based analysis is rapidly gaining acceptance in areas of moderate seismicity.

In the performance-based analysis of landfill response to strong ground shaking, a performance criterion is established in terms of maximum allowable calculated permanent seismic displacement. The performance analysis may be conducted as either a decoupled analysis or as a fully coupled analysis, as explained below.

Decoupled Approach

The *decoupled* approach to seismic analysis was originally developed by Seed and Martin (1966) for earth dams. The approach was further improved by Ambraseys and Sarma (1967), and Makdisi and Seed (1978). Since promulgation of Subtitle D in 1993, this approach has been used for seismic design and analysis of existing landfills (e.g., Kavazanjian et al., 1995; Augello, et al., 1995; Kavazanjian and Matasovic, 1995). Recently, this approach has been used to develop a chart (spreadsheet) solution applicable to seismic deformation analysis of modern landfills by Bray and Travasarou (2007).

In the decoupled approach, the deformation potential of the failure (sliding) mass and seismic response of the earthern structure are evaluated independently. The two are then "coupled" together via the Newmark-type (Newmark, 1965) seismic deformation analysis which is based upon double integration of average acceleration of sliding mass above a pseudostatically-evaluated yield acceleration. Even though this decoupled approach is a significant improvement over conventional pseudostatic analysis, it has significant limitations. Furthermore, when compared to more rigorous *fully coupled* seismic deformation analysis methods and results of physical modeling, the decoupled approach has been shown to be generally conservative. Relevant studies include Lin and Whitman (1983), Gazetas and Uddin (1994), Kramer and Smith (1997), Rathje and Bray (1998; 2000), and Wartman et al. (1999; 2003; and 2005). These authors have demonstrated that, when applied to typical waste fills (up to 100 m thick), the decoupled approach typically overestimates the calculated permanent seismic displacements by at least a factor of two.

Indirect improvements of the decoupled approach include a better understanding of dynamic in-plane interface shear strength testing (see above), the ability to test composite liner and cover interfaces at larger displacements, and improvements in selection of design ground motions. The direct improvements include advances in and promulgation of the advanced site response analysis methods (see, e.g., Hashash et al., 2010), improvements to pseudostatic evaluation of yield acceleration, and improvements of the conventional Newmark-type analysis. Improvements in evaluation of the yield acceleration of the sliding mass are modest, at best, and include such improvements as a search for the lowest calculated yield acceleration by means of the conjugated gradient method and composite (straight line – circle, see Figure 12) failure surfaces. However, these improvements typically only marginally affect the results of the seismic deformation analysis.

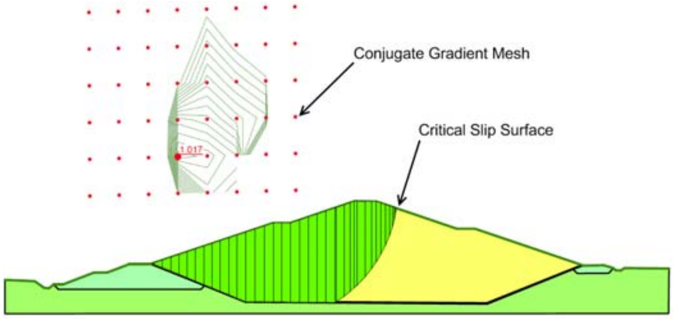

Fig 12. Pseudostatic limit equilibrium analysis of lined landfill with composite failure surface and conjugated gradient method-based search algorithm (GeoSlope International).

Enhancements to the Newmark-type analysis include introduction of the vertical acceleration component into the analysis by Yan et al. (1996) and use of a degrading yield acceleration by Matasovic et al. (1996). Figure 13 schematically compares the conventional Newmark analysis and Newmark analysis with degrading yield acceleration.

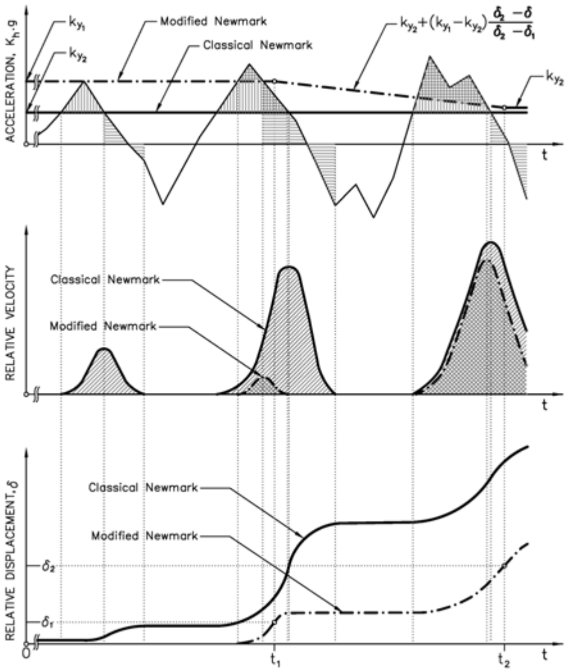

Fig 13. Comparison of the classical and modified (degrading yield acceleration) Newmark-type integration schemes Matasovic et al. 1998).

Matasovic et al. (1998) further extended the Newmark-type analysis to include the effects of two-way sliding. The study by Matasovic et al. (1998) demonstrated that the conventional Newmark-type seismic deformation analysis is conservative when applied to composite liner and cover interfaces with a pronounced difference between peak and residual shear strength. The degree of conservatism depends to a large extent upon the value of the calculated seismic deformation compared to the threshold deformations at which the peak and residual strengths are mobilized.

Fully Coupled Analysis

Fully coupled analysis, with seismic deformation evaluated as an integral part of the site response analysis, is being used with increasing regularity for seismic evaluation and design of dams, wharfs, and earthern structures in areas of high seismicity. However, the implementation of this approach in the seismic design of modern, geosynthetically lined landfills has been slow. This is primarily due to the difficulties associated with modeling of the dynamic behavior of liner and cover interfaces and the assessment of the relevant material properties along those interfaces.

The fully coupled approach is extremely powerful as it allows consideration of the potential beneficial impact of sliding at geosynthetic interfaces on the response of the overlying waste and final cover. It also facilitates direct assessment of the stresses induced in liner system elements. Both are factors not assessed in current state-of-the-practice analyses. The beneficial effect of sliding at an interface, commonly referred to as the "base isolation effect," was first discussed by Kavazanjian et al. (1991) and Yegian and Lahlaf (1992) for geosynthetic base isolation of structures. Kavazanjian and Matasovic (1995) demonstrated by numerical modeling (program D-MOD2000; www.GeoMotions.com), that this beneficial effect significantly reduces the acceleration and displacement response of a waste mass overlying a modern landfill barrier system.

In addition to accommodation of the base isolation effects, the fully coupled approach allows for calculation of dynamically induced stresses and inclusion of the initial static (shear and axial) stress into the analysis. Fowmes et al. (2005) have shown that, even without a dynamic stress increment, the initial static stresses may cause tensile tearing of composite liner components. When seismically-induced shear and axial stresses are superimposed on the static stress, the potential for liner rupture increases. Both the static and seismic components of stress on the liner system have generally been ignored in landfill design. Sometimes, based upon intuition, designers place a "sacrificial" slip layer above a critical interface to limit the shear stress transferred to the liner system and control where slip occurs. The fully coupled approach, however, allows for the stresses and strains on the liner resulting from waste settlement to be included into dynamic analysis and hence the response of the landfill barrier system to be assessed quantitatively.

As a prelude to fully coupled analysis of composite liner system stresses under dynamic loading, Arab et al. (2010) developed a time-domain finite difference model of a rigid block sliding on a plane. A simple elastic-perfectly plastic constitutive model and the Mohr-Coulomb failure criterion was used to simulate the load-displacement behavior of the interface between the block and the plane. This model, illustrated in Figure 14, has been shown by Arab et al. (2010) to accurately reproduce the slip-stick and slip-slip behavior described by Westermo and Udwadia (1983) for frictional sliding of a rigid block on a horizontal plane. The model accurately predicts shaking table tests of a sliding block on horizontal and inclined planes subject to uniform and non-uniform motions provided the appropriate friction angle is used to characterize the interface. Comparison of physical model test results to the results of best-fit numerical analyses demonstrated that the appropriate friction angle may depend upon the velocity of sliding.

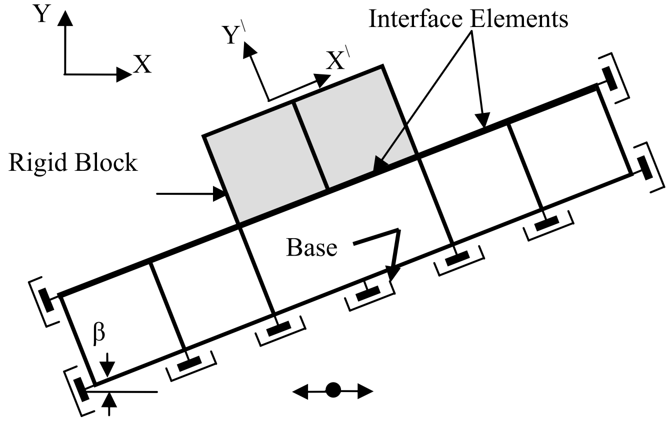

Fig. 14. Finite difference model (only FLAC^{TM} macro elements shown) of an inclined base shaking table test (Arab et al. 2010).

The numerical model by Arab et al. (2010) provides a basis for fully coupled analysis of modern landfills with well-defined sliding surfaces in a more rigorous manner than currently employed in engineering practice. In addition to assessment of the cumulative seismic displacement of landfills, this and similar fully coupled models can be used to evaluate the stress induced in geosynthetic elements of landfill liner and cover systems by strong ground shaking.

STABILITY CRITERIA

Stability criteria are an essential part of seismic analysis and design of modern composite landfill liners and covers. A comprehensive review of stability criteria for seismic design of modern landfills is presented in Kavazanjian et al. (1998).

Although several performance requirements are typically imposed on ancillary structures, the most common seismic design criterion for solid waste landfills is to limit the calculated maximum permanent seismic displacement along liner interfaces to "150 to 300 mm." This criterion, based upon a survey of consulting firms involved in landfill design by Seed and Bonaparte (1992), is commonly referred to as the Seed and Bonaparte stability criterion. At that time, no firm basis was given for the "150 to 300 mm" value other than that it was commonly used in practice. However, this criterion was cited as the accepted seismic performance criterion in the 1995 United States Environmental Protection Agency (EPA) guidance document *RCRA Subtitle D (258) Seismic Design Guidance for Municipal Solid Waste Landfill Facilities* (Richardson et al. 1995).

Subsequent to publication of the 1995 EPA guidance document, several researchers used conventional methods (i.e., decoupled site response and seismic deformation analysis) to conduct back analyses of landfills subject to seismic loading to assess the validity of the Seed and Bonaparte stability criterion. These researchers, including Matasovic et al. (1995), Augello et al. (1995), Matasovic et al. (1998), and Matasovic and Kavazanjian (2006), have found that landfills have survived up to 300 mm of calculated seismic displacement without any visible displacement. Thus, these analyses lend credence to the Seed and Bonaparte performance criterion.

When designing modern, geosynthetically-lined and covered landfills, one should recognize that the Seed and Bonaparte criterion is empirical and is valid only for conventional analysis methods due to the inherent conservatism in such methods. Indeed, if several hundred thousand cubic meters of waste slide 150 mm on top of a geomembrane, it is highly likely that the primary barrier (geomembrane) will tear. Furthermore, transient seismic loads and displacements in the liner system may overstress system components without any visible indications at the ground surface. Therefore, as application of modern, fully-coupled methods gains its acceptance in engineering practice, revision and/or extension of the Seed and Bonaparte criterion will be required. Options include establishment of allowable, seismically-induced strains and/or stresses in geosynthetics components of composite liner systems calculated in fully coupled analyses and limits on landfill surface deformation based upon performance criteria such as drainage. These options are consistent with current regulations that require the landfill containment system withstand – "without damage" – the design earthquake.

CONCLUSIONS AND RECOMMENDATIONS

Modern geosynthetically-lined and covered waste containment facilities are complex and sophisticated engineering systems designed to provide cost-effective waste disposal in a manner that is highly protective of human health and the environment. Changes in waste streams (e.g., due to recycling, waste reduction initiatives, and new products and processes), changes in operational practices at modern landfills (e.g., increased use of alternative daily covers, leachate reinjection, changes in the composition and manufacturing of geosynthetic materials, and the advent of bioreactor technology) suggest that the properties of waste fill and liner materials will continue to evolve for the foreseeable future.

The positive experience with the performance of modern compositely-lined solid waste landfill facilities subject to strong ground shaking (up to approximate bedrock PHGA = 0.4 g), although limited, indicates that these facilities perform well in earthquakes, i.e., can sustain damage to containment system components without a harmful discharge of contaminants to the environment. However, our ability to observe the damage and quantify the stresses and strains induced in the buried components of the modern landfill barrier systems by cyclic loading is still limited.

The seismic design of landfills has evolved since its inception in 1985. Numerous studies have shown that commonly-used de-coupled approach is conservative with respect to assessment of overall deformation. The material parameters required for these analyses (e.g., the dynamic properties of waste) are, following completion of several recent studies, better constrained. The database of material properties, although limited, has expanded. Understanding of the composite liner interface response subject to cyclic (dynamic) loading has improved, while advanced numerical methods for seismic response and deformation analysis are becoming more common. Charts and spreadsheet solutions are based upon hundreds of accelerograms and, if correctly employed, can result in less conservative assessment of landfill seismic performance. However, uncertainty still exists and is related not only to evaluation of design ground motions, but also to numerous factors such as availability of material properties applicable for special wastes, the presence of an initial static shear stress in the liner system induced by waste settlement, the inability to quantify dynamic shear stresses induced in the liner, and a limited ability to test the dynamic shear behavior of the critical elements and interfaces that typically govern the stability of modern landfills.

The concept of allowable seismically-induced deformation provides a rational and practical basis for design of modern waste containment facilities to resist strong ground motion from earthquakes without a harmful discharge of contaminants to the environment. However, whenever possible, allowable deformations should be established on a facility-specific basis due to the many site and project-specific factors that enter into their determination.

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