Journal of Solid Mechanics Vol. 13, No. 3 (2021) pp. 349-365
DOI: 10.22034/jsm.2021.1901384.1602

Study of the Mechanical Behavior of Municipal Solid Waste Landfill Using a Viscoplastic Constitutive Model

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Received 23 June 2021; accepted 25 August 2021

ABSTRACT

As long as there is the need for disposal of household waste there will be the need to understand the phenomena taking place in storage facilities for nonhazardous waste (municipal solid waste landfill). The understanding of landfill technology is of great importance because of its ever-changing state, whether mechanical, chemical or hydrological. In this context, there is a need to better understand the stress-strain behavior evolution with time of the landfilled waste. Based on triaxial and oedometric compression tests of municipal solid waste samples ranging from fresh to degraded waste, a viscoplastic constitutive model (Burgers creep-viscoplastic model) is used to describe the behavior of the municipal solid waste under loading. This model is able to adequately capture the stress-strain and pore water pressure response of the municipal solid waste at different ages. To illustrate its applicability, settlements due to the incremental loading of waste with time are predicted for a typical municipal solid waste landfill. The proposed model predicts the total settlement of a storage facility in a range similar to results published in the literature. An extension of the studied municipal solid waste landfill was also investigated.

Keywords: Municipal waste; Tests; Numerical modelling.

1 INTRODUCTION

THE management of growing quantities of municipal solid waste (MSW) has been a major concern for environmental professionals. Despite recycling and reuse efforts as well as incineration, huge quantities of MSW are still required to be disposed of in engineered landfills. MSW settles under its own weight and as external

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loads are placed on the landfill. External loads include daily soil cover, additional waste layers, final cover, and facilities such as buildings and roads. Significant settlement occurs during and shortly after waste placement due to physical and mechanical processes, which is often referred to as primary settlement. A substantial additional settlement occurs at a slower rate over an extended period of time due to mechanical and biochemical processes, which is often referred to as secondary settlement [43]. Appropriate assessment of MSW landfill settlement has become essential in the current economic and environmental framework. An accurate prediction of the settlements permits to improve the landfill design. It will also enable to optimize the available space and will allow to well manage the post-exploitation land restoration process. Proper forecast of settlement permits maximizing the storage capacity of MSW landfill. However, due to the heterogeneity of MSW, the analysis and design of landfills are complex. The settlement of MSW is mainly attributed to: (1) physical and mechanical processes; (2) chemical processes; (3) dissolution processes; and (4) biological decomposition of organics with time depending on humidity and the number of organics present in the waste [33, 34]. MSW's response in terms of settlement and stability under flow and circulation of leachate depends on the mechanical properties. Knowing the MSW shear strength is necessary to assess the waste slope stability. The mechanisms leading to the waste compaction include physical compression, creep, and the decomposition due to the biodegradation of organic components. In this context, the understanding of the MSW response for modeling the behavior has a considerable importance.A good knowledge of the heterogeneous composition (organic and inorganic material), of the moisture content, of the density, of the distribution of particle size and of the load history permit to reflect the MSW stress-strain behavior. Several collapses of landfills are cited in literature such as, Rumpke in the US failed due to weakness in an underlying shale layer [41], Dona Juana in Colombia due to excess pore pressure [10, 8] and Payatas in the Philippines due to rain [28]. In the literature, several authors have performed drained and undrained triaxial tests. The contributions of [17, 22, 10, 25, 44, 46, 33-35, 12, 1, 40] have permitted to increase the understanding of MSW behavior. Reddy and his co-workers [33-35] presented considerable data on the geotechnical characteristics of MSW in landfills in different degrees of biodegradation which are used for evaluation of models. Researchers have also proposed different constitutive models based on different assumptions. Machado et al [25] proposed a constitutive model to simulate the mechanical behavior of solid urban waste. They considered that MSW's behavior is controlled by two separate parts (the fibers and the matrix) using a coupled elastoplastic model. The matrix is modeled on the basis of the critical state of soil mechanics with a non-associated flow rule. Machado et al [26] improved the previous model, taking into account the influence of organic matter biodegradation on the mechanical behavior of solid urban waste. Babu [1] proposed a constitutive modelto describe the stress-strain behavior of municipal solid waste (MSW) under loading using the critical state soil mechanics framework. The proposed modified cam clay model is extended to incorporate the effects of mechanical creep and time-dependent biodegradation to calculate total compression under loading. This model can be incorporated in numerical simulations to predict the variations of settlement under load with time based on the site-specific conditions. The following assumptions are made in the development of the proposed constitutive model for MSW: (1) The mechanical behavior follows elastoplasticbehavior following critical state soil model framework, with associated flow rule; (2) The secondary compression is governed by the time-dependent phenomenon in exponential function similar to Gibson and Lo [15]; (3) The biological composition is related to time and the total amount of strain that can occur due to biological decomposition. A time-dependent biological degradation is proposed by Park and Lee [31]. This model based on the concept of the critical state is used to understand the response of MSW in undrained conditions. It is validated by a comparison with the experimental data of Reddy et al [33, 34]. Subsequently, Babu et al [2] have shown the applicability of the model for predicting settlement versus time for a typical landfill MSW. Singh and Fleming [40] used a hyperbolic model to predict the stress-strain response of MSW and indicated upper and lower limits. However, Gourc et al [16] presented a one-dimensional biomechanical model to predict the secondary settlement of MSW. In the recent years, to understand the deformation response of landfill structures, analysis using numerical tools such as finite elements and finite differences were done. Bouazza and Pump [9] developed finite element method software. This program makes it possible to model the filling layer by layer of an MSW landfill. The results include the evolution of vertical stresses, compaction, porosity, and density over time. Krishna and al [23] present a two-phase flow numerical model as a tool to predict the hydraulic behavior (moisture distribution and pore fluid pressures) in unsaturated MSW, the mechanical response (stress-strain behavior) and the coupled hydromechanical interactions of MSW in landfills. This model was validated based on field and experimental studies. The addition of leachate in the bioreactor landfills accelerates the decomposition and changes the physical and engineering characteristics of the waste and therefore affects the geotechnical characteristics of the waste mass. Hossain [20] analyzed the behavior of solid waste within bioreactor landfills as a function of time and decomposition using a linear elastic-perfectly plastic constitutive model. Sia et al [38] used the constitutive models implemented in the Flac-2D software: double-elastic for the waste material and the Mohr-coulomb model for the underlying soil, in order to develop a numerical model to study the influence of the variability of the MSW parameters on the integrity mechanisms of the coating system related to the deposition of waste. Babu et al [3] studied the mechanical behavior of MSW on a landfill. In their analysis, an elastic-perfectly plastic model based on the Mohr-Coulomb failure criteria, with an associated flow rule is used . The influence of spatially variable geotechnical properties of MSW on the mechanical behavior of a landfill is investigated. Feng et al [14] proposed a new constitutive model for MSW considering the effect of biodegradation. The indicators representing the degree of biodegradation are first discussed, and the impact of biodegradation on the mechanical properties of MSW is formulated in terms of volumetric strains by introducing a biodegradation-induced void change parameter. It provides a good understanding of the change in waste properties with the long-term biodegradation.

Modelling the settlements and better understanding the mechanical behavior of MSW with time in landfill is still a question of interest. Despite great efforts put on the development of constitutive models, most of the proposed models require a very large number of parameters [1, 2, 13, 18, 19, 26, 27, 29, 30]. Their practical use in the context of landfill design is thus complex and a large uncertainty could remain in the choice of their input parameters. In this article, the stress-strain behavior of MSW is taken into account by using a Burgers-creep viscoplastic model (CVISC). This constitutive model is already implemented in the finite difference software FLAC 2D that requires the use of only eight parameters. A back analysis was done based on classical laboratory experiments, namely oedometer and triaxial compression tests (drained and undrained). Consequently, a landfill cell filled with MSW was simulated. The set of numerical simulations showed that the CVISC is suitable to model the landfill cell behavior taking into account of the construction phases.

2 WASTE BEHAVIOUR DETERMINED BY EXPERIMENTAL TESTS

A database constituted by oedometric tests from Olivier [29] and Stoltz [42] is used to calibrate the parameters of the CVISC model . Thus, triaxial drained and undrained trials on different types of waste [1] are also used to validate and complete the set of parameters.

2.1 Oedometer tests

Olivier [29] carried out two large-scale oedometer tests without and with leachate recirculation (in a $1m^3$oedometer cell). The primary and secondary consolidation settlements were measured during the tests. The loading phase consisted of applying load increments of 10 to 20 *kPa* for a time (Δt) until an ultimate vertical stress of 130 *kPa* (equivalent to the pressure of a 15 meters waste column). The characteristics of each of the two tests are given in Table 1.

For test *n*°1, the setup procedure for the waste was simple: the different constituents of raw MSW were arranged in uniform sub-layers (mono-constituent). Five layers were installed for a total of 442 *kg* of solid waste, to which 66 liters of water were added. The solid and wet volumic weights at the end of filling of the cell are γ_d = 0.521 t/m^3 and γ_w = 0.61 t/m^3, respectively.

For test *n*°2, prior to the waste setup, the bottom of the cell was covered with a geotextile filter to minimize leaching of the solid particles. The waste itself was mixed manually and installed in the tank by layers of 50 *mm*. To simulate the compaction, the various layers of waste were patiently crushed by foot and triturated using a garden claw. After placing a layer (120 *kg* of solid waste, except for the upper half layer 60 *kg*), the waste was preloaded by the application of an uniform vertical stress equal to 40 *kPa*.

The initial part of the settlement curve corresponds to the primary compression phase from 0 to 130 *kPa* followed almost immediately by the rapid discharging phase - recharging necessary for the installation of the riser. After a one hour discharge-recharge cycle, the settlement curve returns to its previous pace, which allowed us to connect the second curve to the first curve (by linear interpolation) [29]. Olivier [29] included voluntarily a limited number of constituents of current nature that has the advantage of being reproducible in any place. A single type of waste was used according to the compositions proposed by Lanini [24] and Thomas [37], i.e 55% of degradable organic waste and 45% of inert or plastic waste. Stoltz [42] carried out short and long-term oedometric tests using cells (around $1m^3$ of waste volume). In these cells, a pressure up to 200 *kPa* can be applied. The cells were sealed to allow an accurate monitoring of the biogas amount produced as a function of time. The cells were specifically designed for long-term tests. A heating system was installed which permits to regulate the temperature up to 60 °*C*.

The waste that has been put in place is a chopped fresh garbage, crushed and screened at 40 *mm* where the composition of the waste is mainly putrescible (59%), paper / cardboard(13%) and plastics(10%). The oedometric tests were done using a wet volumic weight of 0.784 *t/m*^{3} and a dry volumic weight of 0.39 *t/m*^{3}. The loading procedure was the following: 20 *kPa*, 30 *kPa*, 40 *kPa*, 60 *kPa*, 80 *kPa*, 100 *kPa*, 120 *kPa* and 140 *kPa*. Each stage was maintained for 24 hours. Then a phase under constant stress till 330 days was carried out. The cell wall temperature was initially set at 35 °*C*. Table 2 presents the list of the four oedometric tests which will be used for the determination of the CVISC parameters.

Table 1
Specificities of Tests *N*°1 and *N*°2.

Characteristics	Test *N* ° 1: without recirculation	Test *N*° 2: with recirculation
Method of implementation	Partial mixing	Complete mixing of waste
Initial height (h_0)	833 *mm*	845 *mm*
Duration of the test	22 days	7 hours
Height h_1 (130 kPa)	653 *mm*	630 *mm*
Temperature	≅ 25 - 30 ° *C*	≅ 33 - 35 ° *C*

Table 2
Used oedometric tests.

Reference	Application time
Olivier [29]	Short time
	Long time
Stoltz [42]	Short time
	Long time

2.2 Triaxial tests

Triaxial tests realized by Babu et al [1] on two types of MSW samples of 0.5 *m*^{3} and 0.9 *t/m*^{3} density were used in this study: fresh MSW and landfilled MSW. Fresh MSW and landfilled MSW samples were collected from the Orchard Hills landfill (Illinois, USA). The landfilled MSW samples were MSW with 1.5 years of biodegradation.

Undrained triaxial tests were carried out. The samples were isotropically consolidated under different confining pressures of 69, 138, and 276 *kPa*. Pore water pressures were measured during shearing. To ensure uniform pore pressures throughout the specimen, samples were sheared at a constant strain rate (approximately 1% per minute).

Drained triaxial experiments were also conducted on the landfill MSW samples. These samples were isotropically consolidated under different confining pressures of 50, 100, and 150 *kPa*. These twelve tests are listed in Table 3.

Table 3
List of the used triaxial tests (Babu et al [1]).

Test	Waste	Initial effective confining pressure (*kPa*)
Consolidated Undrained Triaxial Tests	Fresh MSW	69
		138
		276
	Landfilled MSW	69
		138
		276
Consolidated Drained Triaxial Tests	Landfilled MSW	50
		100
		150

3 THE NUMERICAL MODEL OF A MUNICIPAL SOLID WASTE STORAGE FACILITY

3.1 Presentation of the storage facility and of the numerical model

The geometry of the waste storage cell is given in Fig.1 and was defined using a typical size of French landfills [7, 29, 4, 42]. The numerical model was implemented with the two-dimensional (2D) finite-difference modeling code FLAC^{2D}. A 2D cross-section was considered and is justified by the fact that the geometry, the boundary conditions and the loading mode (mechanical stresses) are quite similar in all planes parallel to the strain plane of the used cross section. Half the model of the storage facility was considered taking account of the assumption of a symmetrical plane.

The waste storage cell is modelled by using a rectangular mesh. The mesh chosen for materials (waste and soils) is composed of around 10100 volume zones, each having a size between 1 $m \times 1 m$ and 2 $m \times 2 m$ (Fig.1).

The substratum is modelled by using a coarser 2 $m \times 2 m$ mesh that becomes finer at the substratum-waste interface. At the lower side of the substratum, fixed nodal displacements are imposed because of the assumption that, at this depth (21m), the substratum is stiff enough to prevent settlement under the load of the overlying waste backfill. At the sides of the model, the horizontal displacements are fixed; the left and right sides of the model are assumed to be sufficiently far (80 m) from the crest of the landfill cell to avoid the influence of the boundary conditions.

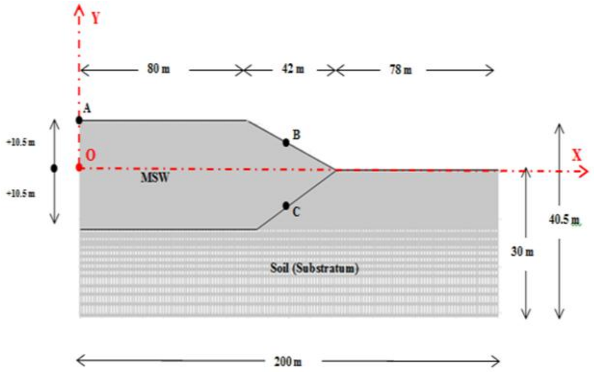


Fig.1
Adopted mesh for the numerical model and dimensions of the MSW landfill.

3.2 Behavior adopted for the materials

Two materials were modelled: the soil foundation and the MSW. The soil of foundation was modeled using a linear elastic-perfectly plastic model with a shear failure criterion of Mohr-Coulomb type. The behavior of the soil foundation is not the center of interest of this study and then a simple constitutive model was adopted. Furthermore, the soil is considered here as a substratum characterized by the values of parameter presented in Table 4.

For the waste and the cover, the Burger-creep viscoplastic model (CVISC) was considered. The CVISC model [32, 6] was adopted in previous works for modelling time-dependent behavior of the weak rock masses. This constitutive model was adopted for the waste behavior due to its capability to describe explicitly the secondary settlement effect. One should note that it does not allow separating the contribution of the biodegradation and of the mechanical creep. The separation between these two processes is, in fact, difficult to do experimentally since they occur simultaneously. The main reason of selecting and using the CVISC constitutive model is its lower number of input parameters when compared to existing models such as the ones proposed by [1, 14].

Table 4
Geomechanical parameters for the soil of foundation.

The used model		Mohr-Coulomb	
Density	ρ	t/m^3	2
Bulk modulus	K	kPa	216667
Shear modulus	G	kPa	38462
Cohesion	C	kPa	8
Friction angle	φ	degree	27

The CVISC model is characterized by a visco-elastoplasticdeviatoricbehavior (Fig.2(b)) and an elastoplastic volumetric behavior (Fig.2(a)). The visco-elastic constitutive law corresponds to a Burger model (Kelvin cell in series with a Maxwell component), and the plastic constitutive law corresponds to a Mohr-Coulomb model. In this model, the visco-elastic strains are deviatoric and depend only on the deviatoric stress $\boldsymbol{S_{ij}}$, instead, the plastic strains are both deviatoric and volumetric and depend on $\boldsymbol{\sigma_{ij}}$ in accordance with the chosen flow rule [6].

The proposed model requires the same parameters as the viscoelastic Burgers model. These parameters are:

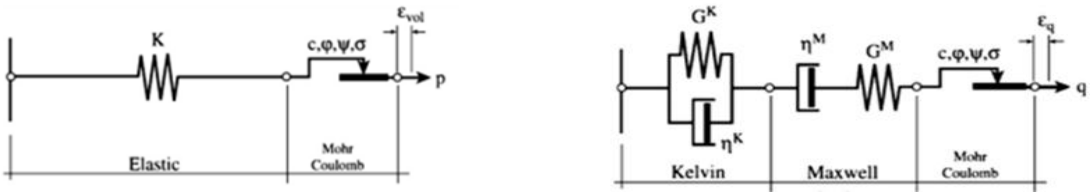
$\boldsymbol{K}$: Kulk modulus;
$\boldsymbol{G}$: Shear modulus;

η: dynamic viscosity.

In addition to these Burgers model's viscoelastic parameters, the Burgers-creep viscoplastic model requires five additional parameters, which are:

σ_t: Tensile limit;
ρ: Volumicweight;
φ: Friction angle;
C: Cohesion
ϕ: Dilatancy angle

The parameters values of the CVISC model will now be estimated from the experimental tests carried out in laboratory presented before.



(a) (b)

Fig.2
Burgers creep-viscoplasticmodel: (a) Elasto-Plastic volumetric model, (b)Visco-elasto-plastic déviatoric model.

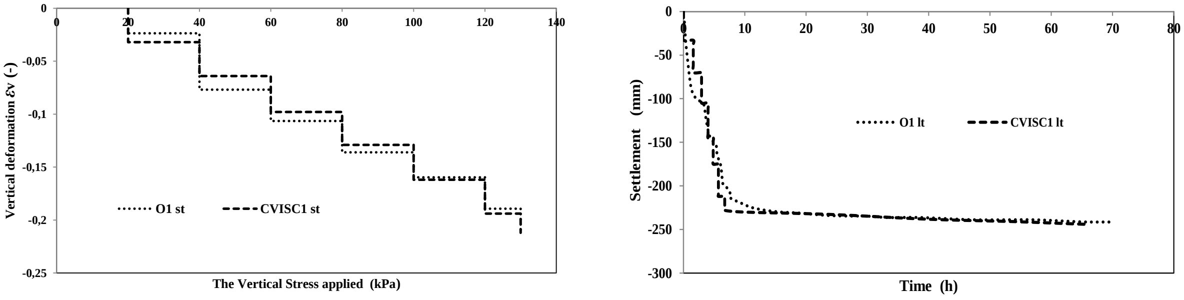
4 BACK ANALYSIS OF THE CVISC PARAMETERS USING THE EXPARIMENTAL TESTS

In order to evaluate the CVISC behavior with representative parameters for MSW, two classical soil tests were modeled with FLAC^{2D} namely oedometricand triaxial tests.

4.1 Oedometer tests modeling

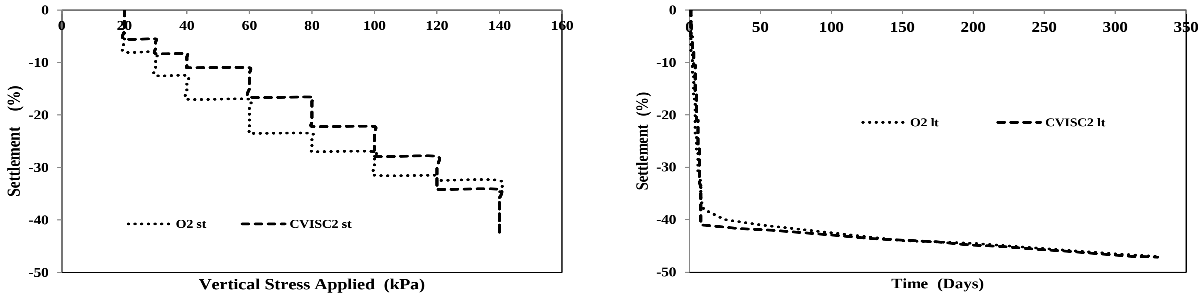
The real oedometric tests were simulated numerically (Fig.3 and Fig.4) for short and long-term which were realized by Olivier [29] and Stoltz [42]. These tests permitted to calibrate the model parameters and to determine the range of values for each parameter (Table 5).

It was found that the viscosity is crucial to adapt the speed of the settlement over time and then to calibrate this setting and have a final settlement similar to the experimental results. This effect is especially sensitive in the case of a long-term test. For the *G* and *K* parameters have an almost negligible effect (a small change in values) on short behavior compared to long-term behavior. While, *φ* and *C* have no effect on short behavior with respect to long-term behavior.



(a) (b)

Fig.3
Modeling and validation of the proposed model with the oedometric (a) and (b) test results realized by Olivier [29].



(a) (b)

Fig.4
Modeling and validation of the proposed model with the oedometric (a) and (b) test results realized by Stoltz [42].

Table 5
CVISC model parameters calibrated on the oedometer tests.

	Authors	Loading time	Density *t/m*^{3}	*G* *kPa*	*K* *kPa*	*C* *kPa*	*φ* (°)	Viscosity *kg/m.s*
Oedometer tests	Olivier [29]	Short term	0.681	305	215	15	36°	2.5×10^8
		Long-term	0.681	270	210	15	36°	4.7×10^8
	Stoltz [42]	Short term	0.784	180	120	15	36°	1.7×10^{10}
		Long-term	0.784	190	125	15	36°	1.7×10^{10}
	The range of values: Short and Long-term		0.681 to 0.784	180 to 305	120 to 215	15	36°	2.5×10^8 to 1.7×10^{10}

4.2 Triaxial compression test modeling

The numerical modeling of a triaxial compression test allows by comparison with experimental tests done in the same conditions to deduce the geomechanical parameters of the CVISC model for MSW. Figs.5 to7shows the comparison between experimental and numerical results for consolidated undrained tests. The considered tests are listed in Table 6.

From these results, it is observed that the deviator values predicted by the model used are higher than the experimental results for tests under a confining pressure of 69 *kPa* and 138 *kPa*.The results also show that the values given by the proposed model are consistent with the behavior observed experimentally on the MSW for a confining pressure of 276 *kPa*.This agreement is assigned to the main feature that the elastic model of Burgers was improved taking into account the plastic behavior using the Mohr-Coulomb plasticity criteria. Similar results were obtained for MSW landfilled.

Table 6
Considered tests.

Test	Waste	Initial effective confining pressure (*kPa*)	Test Reference
Undrained Triaxial	Fresh MSW	69	UDF69
		138	UDF138
		276	UDF276
	Landfilled MSW	69	UDL69
		138	UDL138
		276	UDL276
Drain Triaxial	Landfilled MSW	50	DL50
		100	DL100
		150	DL150
Test	Authors	Time of application	Notation
Oedometric	Olivier [29]	Short time	O1 *st*
		Long time	O1 *lt*
	Stoltz [42]	Short time	O2 *st*
		Long time	O2 *lt*

In general, the values of the deviator obtained from the experimental results continually increase with the increase of axial strain. It suggests that there is not a constraint tip and final failure. This behavior is particularly clear in triaxial drained test (Fig. 7). The values in Table 7 are used to obtain the results shown in Figs. 5 to7, which correspond to the variation of the deviator and pore pressure with the deformation for two different types of waste (fresh MSW, MSW extract a landfill). It can be observed that the proposed model gives a reasonable approximation of the experimental results.

Table 7
CVISC model parameter values calibrated using the triaxial tests.

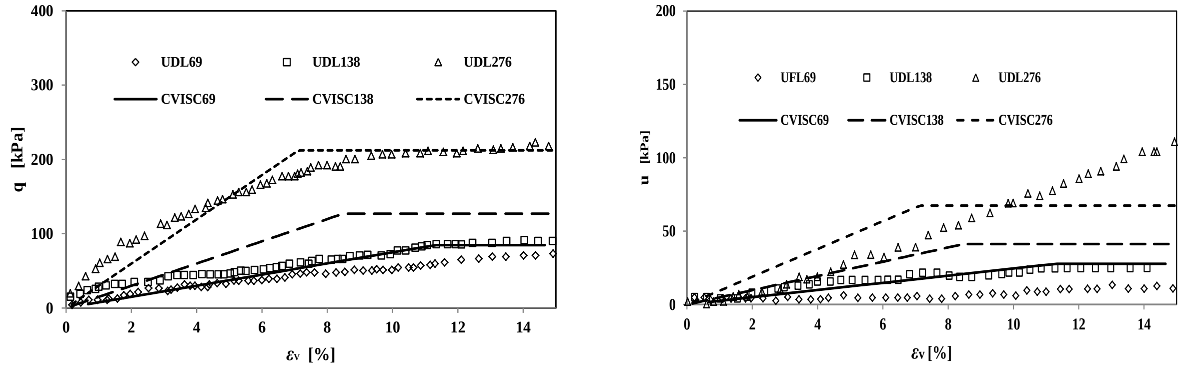
Type Test	Type of waste	Confinement	G	K	C	φ	Viscosity
		kPa	*kPa*	*kPa*	*kPa*	(°)	*kg/m.s*
Consolidated Undrained Triaxial tests	Landfill	69	250	690	20	16 °	4.7×10^8
		138	500	1300	20	16 °	4.7×10^8
		276	1000	2500	20	16 °	4.7×10^8
	Fresh	69	450	600	40	16 °	4.7×10^8
		138	650	1100	40	16 °	4.7×10^8
		276	1000	2000	40	16°	4.7×10^8
	Range of values	69 to 276	250 to 1000	600 to 2500	20 to 40	10.3° to16°	4.7×10^8
Consolidated Drained Triaxial tests	Landfill	50	450	600	60	30°	4.7×10^8
		100	720	1300	60	30°	4.7×10^8
		150	1000	2000	60	30°	4.7×10^8
	Range of values	50 to 150	450 to 1000	600 to 2000	60	30°	4.7×10^8

It is noted that the *G* and *C* parameters of an old waste are less low compared to those of a fresh waste, whereas the parameter *K* increases with the progression of the waste over time. On the other hand, the parameters *G* and *K* increase with the increase of the confinement constraint. For the angle of friction is not influenced by the age of the waste or by the confinement constraint. For the short-term tests the parameter, it is found that the viscosity parameter does not have much influence, for that we took the same value.

The Table.8 presents the values of the parameters of the CVISC model adapted to the waste materials after calibration of the model using triaxial and oedometric tests.

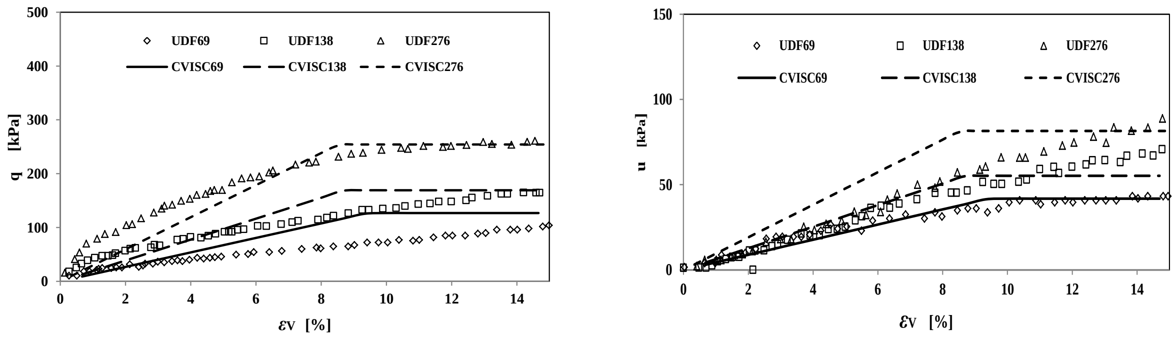
Table 8
The values of the parameters of the CVISC model adapted to the waste materials.

	Density	G	K	C	φ	Viscosity
	t/m³	*kPa*	*kPa*	*kPa*	(°)	*kg/m.s*
Global range of values	0.681 to 1.00	180 to 1000	120 to 2500	15 to 60	10.3° to 36°	2.5×10^8 to 1.7×10^{10}



(a) (b)

Fig.5
Comparison of (a) stress-strain and (b) pore water pressure response based on the proposed model and undrained triaxial experiments for landfilled MSW.



(a) (b)

Fig.6
Comparison of (a) stress-strain and (b) pore water pressure response based on the proposed model and undrainedtriaxial experiments for fresh MSW.

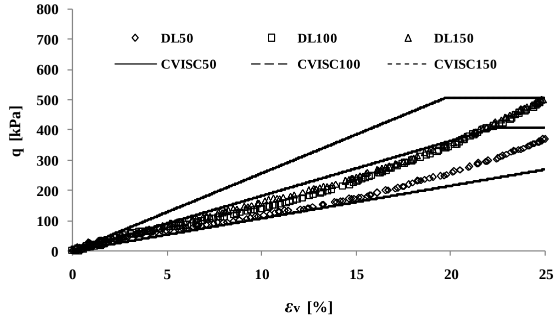


Fig.7
Comparison of stress-strain response based on the proposed model and drained triaxial experiments for landfilled MSW.

5 SIMULATION OF A LANDFILL CELL

5.1 Filling process

Phase 1: The excavation of the cell till level -10.5*m* is done. This phase has no time duration because it only affects the soil material modeled by the Mohr-Coulomb model that does not depend on time. The movements are reset at the beginning of phase 2.

Phase 2: Filling of the landfill cell. The filling time for each layer is based on the typical operating time of the landfill cells in France. A period of 45 days is used for filling each 3.5*m* thick layer. Each layer is divided into 7 sub-layers of 0.5*m* thickness (initial height of each mesh layer).

This filling phase is based on the following assumptions:

- Compaction phases are not defined because these additional phases would require step-by-step work and is not well known. The application of the consolidation state for each additional layer was used (preferred);
- The power generated by the compaction with the rollers is assumed to generate the same pre-consolidation stress over the entire height of the layer [29];
- The above assumptions therefore require a unit weight value to be set after the compaction of the municipal solid waste;
- The three previous assumptions lead to the fact that the immediate settlement, when the material is pre-compacted by compactors, is ignored;
- The filling of the landfill cell is assumed to be continuous for 270 days (45 days × 6 layers) and without breaks. In real works, the soil is sometimes added between the layers of MSW to improve the stability of the body and to avoid the wind propagation. This practice was not modelled;
- Parameters, like *G* (the shear modulus) and *K* (the bulk modulus) of the CVISC model for the MSW are modified from one layer to another to consider the confinement effect (the weight of the upper layers) on the physical properties of the waste materials. These two parameters increase with the depth (confinement) of the waste in the cell;
- Post-closure follow-up phase: the cell behavior is simulated during 30 years to estimate the settlement during a typical post-closure duration.

5.2 Geomechanical parameters of the MSW

Young's modulus *E* increases with depth and confining stress [5, 11, 39]. In the literature, the value of the elastic modulus *E* is generally considered ranged between 0.5*MPa* and 7*MPa* [36]. Fig. 8 shows the applied values *E* with the depth in the studied cell. The Young's modulus is calculated using the range of values of *G* and *K* given Table 7. Its linear variation ranges between 448 *kPa* at the top of the cell to 2915 *kPa* at the bottom.

The material properties are defined for the MSW and the foundation soil as specified in Table 9.

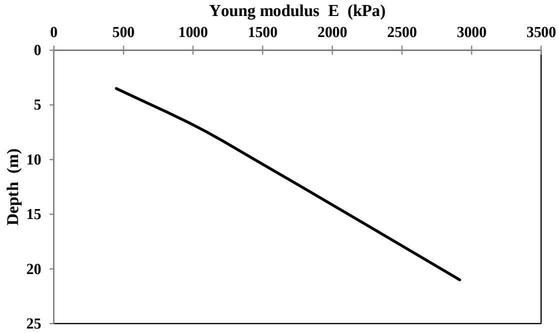


Fig.8
Variation of the MSW Young modulus with the depth.

Table 9
Material models parameter.

The material waste			
Constitutive Model		CVISC	
The parameter	Notation	Unity	Value
Density	ρ	t/m^3	0.9
Bulkmodulus	K	kPa	120 à 2325
Shearmodulus	G	kPa	250 à 1130
Cohesion	C	kPa	15
Friction angle	φ	Degree	36°
Viscosity	μ	$kg/m.s$	7×10^8
Tensilelimit	σ_t	kPa	10^7
Soil (Substratum)			
Constitutive Model		Mohr-Coulomb	
Density	ρ	t/m^3	2
Bulkmodulus	K	kPa	216667
Shearmodulus	G	kPa	38462
Cohesion	C	kPa	8
Friction angle	φ	Degree	27

5.3 Results of the reference case

The landfill cell presented on Fig.1 (reference case) was modelled to assess the CVISC model's ability to simulate the mechanical behavior of MSW at the site scale. The Fig.1 shows the position of the studied points (point *A, B* and *C*).

5.3.1 Vertical deformationevolution

A maximum compaction of 8 *m* (≈ 38.3%) after the post-exploitation period was obtained after a 30 years period after the end of the final cover installation with 1,05 *m* (≈ 5%) due to the primary settlement and instantaneous settlement (Fig. 9). Wall & Zeiss [45] estimated the total settlement in the discharge of untreated MSW between 25% and 50% after 30 years of its exploitation. One should note that the creep model predicts a very linear secondary settlement phase. It is then probably unrealistic when the very long period is studied.

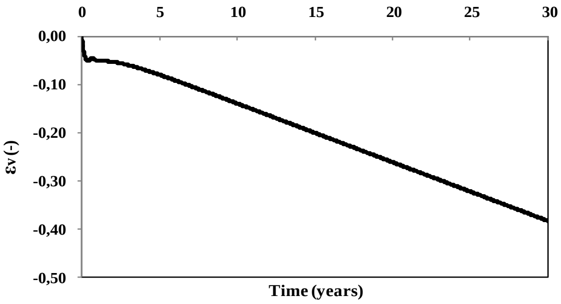


Fig.9
Evolution of the vertical deformation of point *A* on a long time.

5.3.2 Shearstrainevolution

The evolution of the shear deformation ε_{xy} of the point *C* is very fast at the beginning and reaches a constant value at a time of around 2 years from the date of implementation of the last layer (6*th* layer) (Fig. 10).

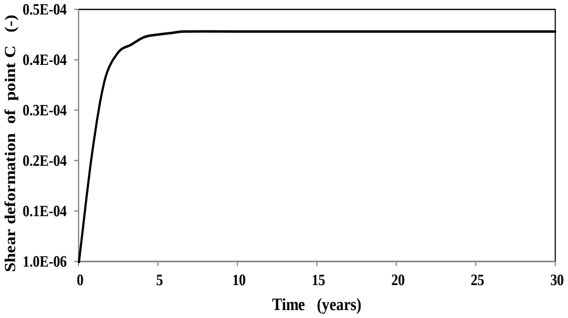


Fig.10
Evolution of the shear deformation of point C on a long time.

5.4 Influence of the MSW parameters

After the presentation of the reference case, the influence of several parameters was investigated by using a parametric study on the MSW parameters:

- Young modulus;
- Volumicweigth;
- Viscosity.

5.4.1 Influence of the MSW Young modulus

To study the effect of Young's modulus variation with depth, a parametric study was carried out on three set of parameters (*E1, E2*, and *E3* in Table 10).

Table 10
The three studied ranges of Young's modulus variation *E* with depth (*Z*).

Range	The value range of Young's modulus *E* (*MPa*)	Depth *Z* (*m*)
E1	0,448*MPa* (at *Z*=0*m*) to 1 *MPa* (at *Z* =21 *m*)	0 to 21
E2	0,448 *MPa* (at *Z* =0 *m*) to 5 *MPa* (at *Z* =21 *m*)	
E3	0,448 *MPa* (at *Z* =0 *m*) to 7 *MPa* (at *Z* =21 *m*)	

Fig. 11 shows that the variation range of Young's modulus has mainly an effect on the value of the instantaneous and of the primary settlement but it has no effect on the kinetics of the creep deformations. The 3 curves are parallel.

Fig. 12 shows that Young's modulus variation range has a small effect on the final maximum value of the shear deformation. It has only a weak effect during the first five years of the simulation. A lower value of Young's modulus, corresponding to a softer material, induces a quicker increase of the shear deformation.

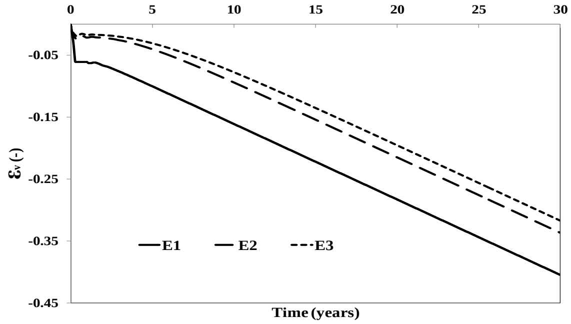


Fig.11
The impact of the value range of Young's modulus E on the vertical displacement of the Point *A*.

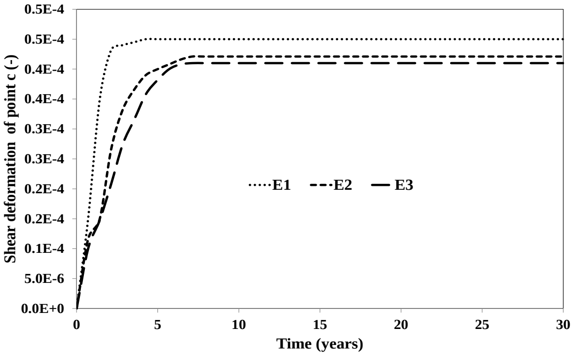


Fig.12
Impact of the value range of Young's modulus E on the shear deformation of point *C*.

5.4.2 Influence of the MSW Volumicweigth

It can be seen from Fig. 13 that the primary and instantaneous settlements slightly increase with density. This effect is also sensitive to the creep settlement kinetics. A heavier material promotes a faster settlement if all other material parameters are kept constant.

The MSW Volumicweight also has a significant effect on the final value of the shear deformation but does not influence the general shape of the evolution curve of this deformation with time (Fig. 14).

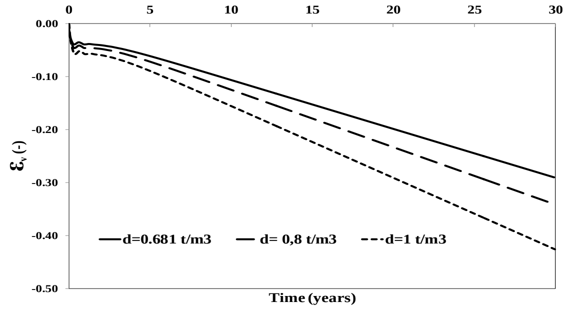


Fig.13
The impact of the MSW Volumicweigth on the vertical displacement of the Point *A*.

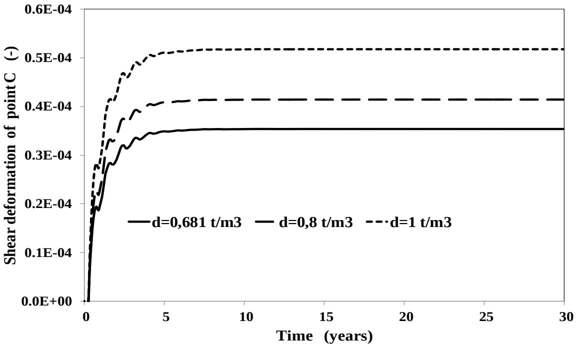


Fig.14
The impact of the MSW Volumicweigth on the shear deformation of point *C*.

5.4.3 Impact of the viscosity on the vertical displacement

The influence of viscosity on the landfill cell movements was studied using the numerical model. Fig.16 shows the strong influence of the viscosity on settlements. The viscosity does not influence the deformation values caused by loading; contrariwise it strongly contributes to the acceleration of the long-term settlement (creep). Fig. 15 shows the distribution of the vertical displacement of the landfill cell after 30 years. It is also observed that the crest of the embankment settles around 10 *m* and that the slope itself tends to swell.

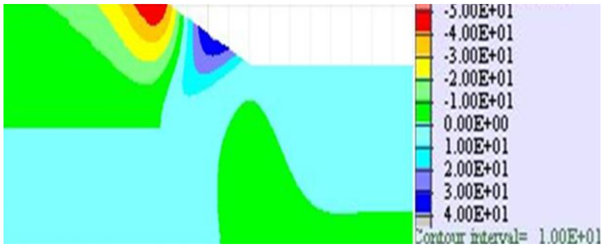


Fig.15
The distribution of the vertical displacement in the waste material.

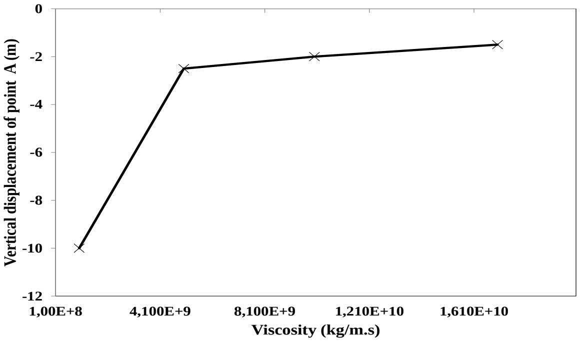


Fig.16
The impact of viscosity on the vertical displacement of the Point *A*.

5.4.4 Impact of the viscosity on the horizontal displacement

To see the impact on the mechanical behavior, the influence of the viscosity on the horizontal displacement at the point *B* is presented in Fig. 18. The horizontal displacement decreases with increasing viscosity. Fig. 17 shows the distribution of the horizontal displacement in the landfill cell after 30 years. It also shows that the maximum horizontal displacement is located at point *B*.

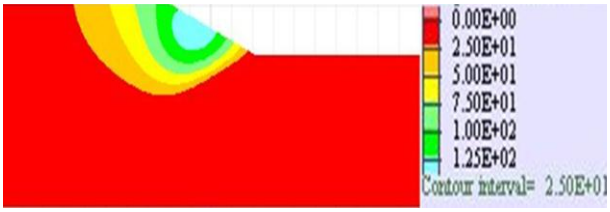


Fig.17
The distribution of horizontal displacement in the waste material.

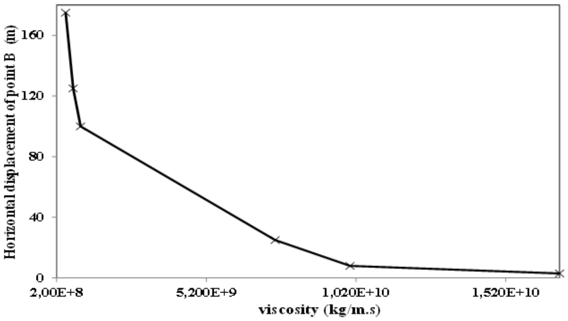


Fig.18
Impact of the MSW viscosity on the maximum horizontal displacement (Point *B*).

5.4.5 Impact of the viscosity on the shear deformation

The shear deformation at point *C* decreases an order of magnitude in the studied viscosity range (Fig. 20). For viscosities higher than 5.2×10^9 *kg/m.s* this effect tends to decrease. With such high values of viscosity, the waste material has the tendency to flow and slip out of the cell on the slope side. The increase in viscosity increases the slip between the constituents of the matrix of the waste material. Fig.19 shows the value and distribution(at 30 years) of the shear deformation of the landfill cell and also shows that the maximum shear deformation is located at point *C*.

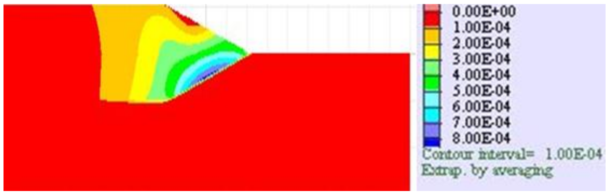


Fig.19
The distribution of the shear deformation in the waste material.

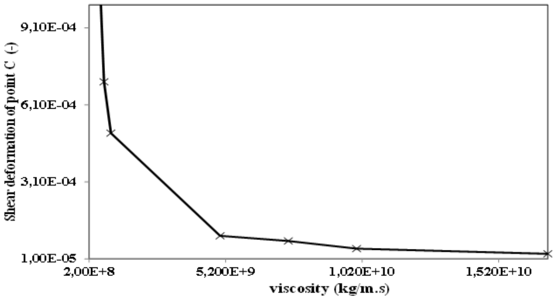


Fig.20
Impact of the MSW viscosity on the shear deformation of point *C*.

5.5 Study of the extension of the cell

The settlement in the studied cell reaches approximately 8*m* after 30 years. For optimal use of the cell, it is proposed to reuse its space by adding four layers of a waste of 9 kN/m^3 density and 2*m* thick each (4 × 2*m* = 8*m*: equivalent to the final settlement of the first 1).To predict the behavior of the cell (packing), four loading phases were applied to the model. Each loading phase has a duration of 25 days (Fig. 21). The final settlement after the recharge of the cell with these last three layers reaches 14.13*m* (67.3%) (Fig. 22). Fig. 22 shows the evolution of the settlement over time (the life of the waste cell is taken equal to 60 years).

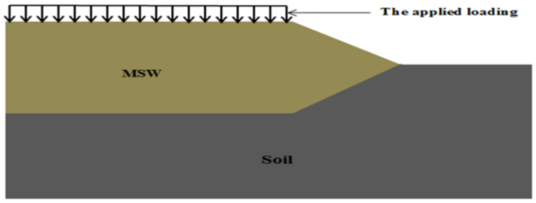


Fig.21
Diagram showing the point of application of the loading on the waste.

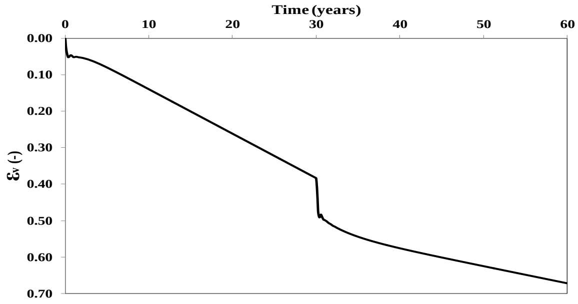


Fig.22
Evolution of settlement after the addition of three additional layers (1.5*m* thick).

6 CONCLUSIONS

A simple constitutive model is proposed to study the mechanical behavior of municipal or urban solid waste MSW based on an extension of the viscoelastic model of Burgers. A comparison of the stress-strain responses an dinterstitial pressure-strains between the experimental results and the results to model two different types of MSW has demonstrated that the proposed model can simulate the behavior of MSW in a satisfying manner.

The tests permit to calibrate the model parameters and determine their value ranges for a proper use to simulate and predict the mechanical behavior of waste material at different ages.

The use of the CVISC constitutive model for MSW landfill gave comparable results to the results of literature. A vertical deformation of 38.3% is obtained after 30 years of operation. The application led to consider the viscosity parameter, to pass from short-term to long-term.

The results of the 2D landfill cell simulation show that:

- The viscosity does not influence the deformation values caused by loading; contrariwise it strongly contributes to the acceleration of the long-term settlements due to creep,
- A higher viscosity tends to limit the horizontal displacement,
- The value of the shear deformation ε_{xy} increases quickly during the filling phase and reaches a constant value about two years after the implementation of the last layer,
- The variation range of Young's modulus has a main effect on the value of the instantaneous and primary settlement but it has no effect on the kinetics of the creep deformations,
- The variation of Young's modulus has a small effect on the final maximum value of the shear deformation and on the evolution of the shear deformation with time,
- The extension of the cell is possible and the cumulative settlement reaches (67.3%) after 60 years.

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