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Non-associated Constitutive Law of Soils and its Simulation Based on the Bi-potential Theory*

Y-J. Zhou ^a, Z-Q. Feng ^{a,b}, W-Y. Xu ^a

Abstract—This paper is devoted to study the non-associated constitutive law of soil materials and to construct a bi-potential for the classical Drucker-Prager (D-P) plastic model. It can be proved that the bi-potential not only satisfies the constitutive relationship of the D-P model, but also conforms to the non-associated flow rule. We present the relevant algorithms for the integration of soil constitutive equations. Two simple numerical examples illustrate the rationality of the bi-potential theory and the feasibility of its algorithm.

Keywords—Bi-potential, D-P model, Algorithm, Simulation

I. Introduction

Material nonlinearity plays an important role in solid mechanics. The rationality and accuracy of material nonlinearity theory are the basis of theoretical analysis and simulation of materials and structures. For classical materials such as metal, the yield potential is associated with the flow potential. Its theory is relatively well established. But for the non-associated materials such as soils, the yield potential is different from the flow one. Conventional model uses two independent functions to express the potentials [1]. Nowadays, the theory on associated materials is relatively well established and its simulation becomes mature. The return-mapping algorithm is a widely accepted and applied method to integrate constitutive laws of associated materials [2]. For non-associated materials, the yield potential is different from the flow one. De Saxcé uses Legendre transformation to deal with this kind of laws [3]. The bi-potential theory is put forward in [4] and the theory is applied to the non-associated material successfully. In [5] and [6], the bi-potential function has been proved to be able to express the flow rule of soils more clearly. The bi-potential theory is suitable to solve the set problems and can be used to build the constitutive laws of non-associate materials. Material like soils is a kind of non-associated materials, whose mechanical behavior is very complex. This paper summarizes previous relevant works, choosing the classical three-parameter soil D-P model to build its constitutive relationship under within the bi-potential framework. This theory leads to a simple and efficient algorithm for the numerical integration of non-associated constitutive laws.

II. D-P model

The D-P model is given in [7] and illustrated in Figure 1. In order to simplify the problem, the ideal plastic D-P model is used in this paper. This model is represented by a pair of conjugate tensor $\boldsymbol{\sigma} = (s, s_m)$ and $\dot{\boldsymbol{\epsilon}}^p = (\dot{\epsilon}^p, \dot{\epsilon}_m^p)$, in which $s_m = 1/3 \cdot Tr(\boldsymbol{\sigma})$ is the mean stress, $\mathbf{s} = \boldsymbol{\sigma} - s_m \mathbf{1}$ the stress deviator tensor, $\dot{\epsilon}_m^p = Tr(\dot{\boldsymbol{\epsilon}}_m^p)$ the trace of the plastic strain rate tensor, $\dot{\boldsymbol{\epsilon}}^p = \dot{\boldsymbol{\epsilon}}^p - 1/3 \cdot \dot{\epsilon}_m^p \mathbf{1}$ the deviator tensor and $\mathbf{1}$ the second order unity tensor.

During all the process, the stress must be in the stress cone K_σ defined by

$$K_\sigma = \{(s_m, s) \mid \|s\|/k_d + s_m \tan \phi \leq c\} \quad (1)$$

where c is the cohesion, ϕ the friction angle, k_d a constant, $\|\cdot\|$ the Euclidean norm.

The flow rule of D-P model is limited in the plastic strain rate cone K_ϵ , which can be represented by two parts: the regular set K_r and the apex set K_a .

$$K_r = \{(\dot{\epsilon}_m^p, \dot{\boldsymbol{\epsilon}}^p) \mid \dot{\epsilon}_m^p \geq k_d \tan \theta \|\dot{\boldsymbol{\epsilon}}^p\|\} \quad (2)$$

$$K_a = \{(\dot{\epsilon}_m^p, \dot{\boldsymbol{\epsilon}}^p) \mid \dot{\epsilon}_m^p \geq k_d \tan \phi \|\dot{\boldsymbol{\epsilon}}^p\|\} \quad (3)$$

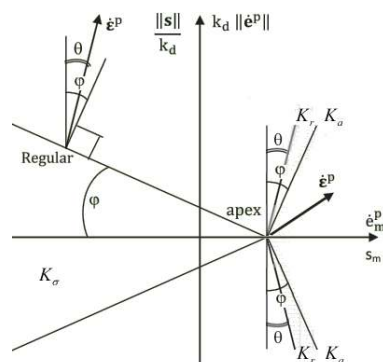


Figure 1 D-P model cones

As is known in [7], the D-P model is the implicit standard material. It is clear that the plastic strain rate is not orthogonal to the yield surface, so the conventional orthogonal law is not applicable. Form above, the theory of bi-potential gives the strain rate component of projection,

$$\dot{\boldsymbol{\epsilon}}^p = (\dot{\boldsymbol{\epsilon}}^p, \dot{\epsilon}_m^p + k_d (\tan \phi - \tan \theta) \|\dot{\boldsymbol{\epsilon}}^p\|) \quad (4)$$

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Equation (4) can be written as a differential collection set form to express the flow rules of D-P model. The detailed proofs are given in [9].

$$(\dot{\mathbf{e}}^p, \dot{\mathbf{e}}_m^p + kd(\tan \phi - \tan \theta) \|\dot{\mathbf{e}}^p\|) \in \partial \Psi_{K_c}(\boldsymbol{\sigma}) \quad (5)$$

III. Bi-potential for soils

In [3], the bi-potential for both explicit and implicit standard material is introduced in detail. So, the rate form and increment form bi-potential for D-P model can be obtained.

A. Rate form

1) Elasticity

When D-P model is in elastic state, it can be considered as an explicit standard material. At this time

$$b_e(\dot{\mathbf{e}}^e, \boldsymbol{\sigma}) = \varphi_e(\dot{\mathbf{e}}^e) + \varphi_e^*(\boldsymbol{\sigma}) \geq \dot{\mathbf{e}}^e \cdot \boldsymbol{\sigma} \quad (6)$$

Moreover, the model satisfies the elastic constitutive laws

$$\varphi_e(\dot{\mathbf{e}}^e) = \dot{\mathbf{e}}^e [\mathbf{D}^e] \dot{\mathbf{e}}^e / 2 = K_c (\dot{\mathbf{e}}_m^e)^2 / 2 + \mu \|\dot{\mathbf{e}}^e\|^2 \quad (7)$$

$$\varphi_e^*(\boldsymbol{\sigma}) = \boldsymbol{\sigma} [\mathbf{D}^e]^{-1} \boldsymbol{\sigma} / 2 = (s_m)^2 / 2 K_c + \|\mathbf{s}\|^2 / 4 \mu \quad (8)$$

The bi-potential function can be obtained under the elastic state,

$$b_e(\dot{\mathbf{e}}^e, \boldsymbol{\sigma}) = K_c (\dot{\mathbf{e}}_m^e)^2 / 2 + \mu \|\dot{\mathbf{e}}^e\|^2 + (s_m)^2 / 2 K_c + \|\mathbf{s}\|^2 / 4 \mu \quad (9)$$

Where K_c and μ are respectively the bulk and shear modulus. Equation (9) can be easily verified to meet the orthogonal law

$$\dot{\mathbf{e}}^e = \partial \varphi_e^*(\boldsymbol{\sigma}) = \partial_s b_e(\dot{\mathbf{e}}^e, \boldsymbol{\sigma}) \quad \text{and} \quad \boldsymbol{\sigma} = \partial \varphi_e(\dot{\mathbf{e}}^e) = \partial_s b_e(\dot{\mathbf{e}}^e, \boldsymbol{\sigma}) \quad (10)$$

2) Plasticity

When D-P model is in plastic state, it can be considered as an implicit standard material. At this time,

$$b_p(\dot{\mathbf{e}}^p, \boldsymbol{\sigma}) \geq \dot{\mathbf{e}}^p \cdot \boldsymbol{\sigma} \quad (11)$$

$\dot{\mathbf{e}}^p \cdot \boldsymbol{\sigma}$ can be decomposed as,

$$\boldsymbol{\sigma} \cdot \dot{\mathbf{e}}^p = s_m \cdot \dot{\mathbf{e}}_m^p + \mathbf{s} \cdot \dot{\mathbf{e}}^p \quad (12)$$

The first item of (12) can be rewritten as follow,

$$s_m \cdot \dot{\mathbf{e}}_m^p = c \dot{\mathbf{e}}_m^p / \tan \phi + (s_m - c / \tan \phi) \dot{\mathbf{e}}_m^p \quad (13)$$

Equation (1) and (2) give,

$$s_m \cdot \dot{\mathbf{e}}_m^p \leq c \dot{\mathbf{e}}_m^p / \tan \phi + k_d \tan \theta (s_m - c / \tan \phi) \|\dot{\mathbf{e}}^p\| \quad (14)$$

For the second item of (12), considering the Cauchy-Schwarz inequality and the relationship (1), another inequality is given by

$$\mathbf{s} \cdot \dot{\mathbf{e}}^p \leq \|\mathbf{s}\| \cdot \|\dot{\mathbf{e}}^p\| \leq -k_d \tan \phi (s_m - c / \tan \phi) \|\dot{\mathbf{e}}^p\| \quad (15)$$

So, in the case of plastic flow, the plastic bi-potential can be obtained by combining (11), (12), (13) and (14).

$$b_p(\dot{\mathbf{e}}^p, \boldsymbol{\sigma}) = c \dot{\mathbf{e}}_m^p / \tan \phi + k_d (\tan \theta - \tan \phi) (s_m - c / \tan \phi) \|\dot{\mathbf{e}}^p\| \quad (16)$$

The flow rule of D-P model under plastic stage could also be verified.

$$\dot{\mathbf{e}}^p \in \partial_s b_p(\dot{\mathbf{e}}^p, \boldsymbol{\sigma}) \quad (17)$$

B. Incremental form

According to the incremental relationships

$$\Delta \boldsymbol{\varepsilon} = \Delta t \cdot \dot{\boldsymbol{\varepsilon}}, \quad \Delta \boldsymbol{\sigma} = \boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_0 \quad (18)$$

The subscript 0 indicates the initial iteration and the subscript 1 stands for the final iteration. According to relationships above, the incremental bi-potential function of the D-P model can be built.

1) Elasticity

According to (6) and (18), $\Delta b_e(\Delta \boldsymbol{\varepsilon}^e, \Delta \boldsymbol{\sigma})$ is defined as

$$\Delta b_e(\Delta \boldsymbol{\varepsilon}^e, \Delta \boldsymbol{\sigma}) = \Delta \varphi_e(\Delta \boldsymbol{\varepsilon}^e) + \Delta \varphi_e^*(\Delta \boldsymbol{\sigma}) \geq \Delta \boldsymbol{\sigma} \cdot \Delta \boldsymbol{\varepsilon}^e \quad (19)$$

So, under the condition of elastic constitutive, the incremental elastic bi-potential of D-P model is

$$\Delta b_e(\Delta \boldsymbol{\varepsilon}^e, \Delta \boldsymbol{\sigma}) = \frac{K_c}{2} (\Delta \boldsymbol{\varepsilon}_m^e)^2 + \mu \|\Delta \boldsymbol{\varepsilon}^e\|^2 + \frac{1}{2 K_c} (\Delta s_m)^2 + \frac{1}{4 \mu} \|\Delta \mathbf{s}\|^2 \quad (20)$$

2) Plasticity

In the period of time Δt , the plastic bi-potential must satisfy

$$\Delta b_p(\Delta \boldsymbol{\varepsilon}^p, \Delta \boldsymbol{\sigma}) \geq \Delta \boldsymbol{\varepsilon}^p \cdot \Delta \boldsymbol{\sigma} \quad (21)$$

Furthermore,

$$\Delta \boldsymbol{\varepsilon}^p \in \partial_s b_p(\Delta \boldsymbol{\varepsilon}^p, \boldsymbol{\sigma}_0 + \Delta \boldsymbol{\sigma}) \quad (22)$$

$$\Delta \boldsymbol{\sigma} \in \partial_{\Delta \boldsymbol{\varepsilon}} b_p(\Delta \boldsymbol{\varepsilon}^p, \boldsymbol{\sigma}_0 + \Delta \boldsymbol{\sigma}) - \boldsymbol{\sigma}_0 \quad (23)$$

Thus the $b_p(\Delta \boldsymbol{\varepsilon}^p, \Delta \boldsymbol{\sigma})$ can be expressed as

$$\Delta b_p(\Delta \boldsymbol{\varepsilon}^p, \Delta \boldsymbol{\sigma}) \geq b_p(\Delta \boldsymbol{\varepsilon}^p, \boldsymbol{\sigma}_0 + \Delta \boldsymbol{\sigma}) - \boldsymbol{\sigma}_0 \cdot \Delta \boldsymbol{\varepsilon}^p \quad (24)$$

So, under the condition of plastic flow, the incremental plastic bi-potential of the D-P model is given by

$$b_p(\Delta \boldsymbol{\varepsilon}^p, \Delta \boldsymbol{\sigma}) = c \Delta \boldsymbol{\varepsilon}_m^p / \tan \phi + k_d (\tan \theta - \tan \phi) (s_{m_0} + \Delta s_m - c / \tan \phi) \|\Delta \boldsymbol{\varepsilon}^p\| - s_{m_0} \Delta \boldsymbol{\varepsilon}_m^p - s_0 \Delta \boldsymbol{\varepsilon}^p \quad (25)$$

3) Elastoplasticity

$$\Delta s_m = K_c (\Delta e_m - \Delta e_m^p) - \Delta s_m \rightarrow 0 \quad (40)$$

Because $\|\Delta \mathbf{e}^p\|$ must be nonnegative, so we can get the plastic yield criterion at regular point of the D-P model

$$\|\mathbf{n}_0 + \Delta \mathbf{e}\| - \varepsilon_d \{c - \tan \varphi (s_{m0} + \Delta s_m) + \tan \theta (\Delta s_m - K_c \Delta e_m)\} \geq 0 \quad (41)$$

2) Apex point

An apex point has the following characteristics

$$s_m = c / \tan \varphi \quad \text{and} \quad \|\mathbf{s}\| = 0 \quad (42)$$

Updating $(\Delta \varepsilon^p, \Delta \sigma)$ at an apex point in elastic stage is the same as that at a regular point.

When the apex point under the plastic phase, (42) is satisfied, then

$$\|\Delta \mathbf{e}^p\| = \|\mathbf{n}_0 + \Delta \mathbf{e}\| = \|\mathbf{s}_0 + 2\mu \Delta \mathbf{e}\| / 2\mu \quad (43)$$

So, $(\Delta \varepsilon^p, \Delta \sigma)$ can be explicitly expressed,

$$\Delta \mathbf{e}^p = \|\Delta \mathbf{e}^p\| \mathbf{n} \quad \text{and} \quad \Delta e_m^p = (s_{m0} + K_c \Delta e_m - c / \tan \varphi) / K_c \quad (44)$$

$$\Delta \mathbf{s} = 2\mu (\Delta \mathbf{e} - \Delta \mathbf{e}^p) \quad \text{and} \quad \Delta s_m = K_c (\Delta e_m - \Delta e_m^p) \quad (45)$$

Because $\partial L / \partial \Delta e_m^p = 0$, the plastic yield criterion at apex point of the D-P model is given by

$$k_d \tan \theta \|\mathbf{n}_0 + \Delta \mathbf{e}\| - (s_{m0} + K_c \Delta e_m - c / \tan \varphi) / K_c \leq 0 \quad (46)$$

D. Elastoplastic matrix

According to the definition of elastoplastic matrix

$$\mathbf{D}_{ep} = \partial \Delta \sigma / \partial \Delta \varepsilon \quad (47)$$

Because of the implicit expression of the incremental stress and incremental strain, the elastoplastic matrix at regular point and apex point can be represented as a unity

$$\mathbf{D}_{ep} = \frac{\partial \Delta \sigma}{\partial \Delta \varepsilon} \frac{\partial \Delta \sigma_r}{\partial \Delta \varepsilon} = - \left(\frac{\partial \Delta \sigma_r}{\partial \Delta \varepsilon} \right)^{-1} \frac{\partial \Delta \sigma_r}{\partial \Delta \varepsilon} = (\mathbf{I} - \mathbf{D}_c)^{-1} \mathbf{D}_i \quad (48)$$

1) Regular point

Under elastic stage, the elastoplastic matrix is equal to the elastic matrix.

$$\mathbf{D}_{ep} = \mathbf{D}_c \quad (49)$$

Under plastic stage, the elastoplastic matrix can be calculated by (48) and

$$\mathbf{D}_i = \beta \mathbf{1} \otimes \mathbf{1} / k_d + \alpha (\mathbf{I} - \mathbf{1} \otimes \mathbf{1} / 3) + \delta \mathbf{n} \otimes \mathbf{n} - \beta \tan \theta (\mathbf{1} \otimes \mathbf{n} + \mathbf{n} \otimes \mathbf{1}) \quad (50)$$

$$\mathbf{D}_c = (\beta (\tan \theta - \tan \varphi) \mathbf{n} \otimes \mathbf{1}) / 3 K_c \quad (51)$$

$$\text{with } \alpha = 2\mu \left(1 - \frac{\|\Delta \mathbf{e}^p\|}{\|\Delta \mathbf{e} + \mathbf{n}_0\|} \right), \quad \beta = \frac{1}{1 + \varepsilon_c k_d^2 \tan^2 \theta}, \quad \delta = k_d \beta \tan^2 \theta.$$

2) Apex point

Due to the constraints (42), the elastoplastic matrix at the apex point can be inferred as

$$\mathbf{D}_{ep} = 0 \quad (52)$$

E. Algorithms

1) Constitutive integration

The constitutive integration located at one Gauss point is illustrated in Figure 3.

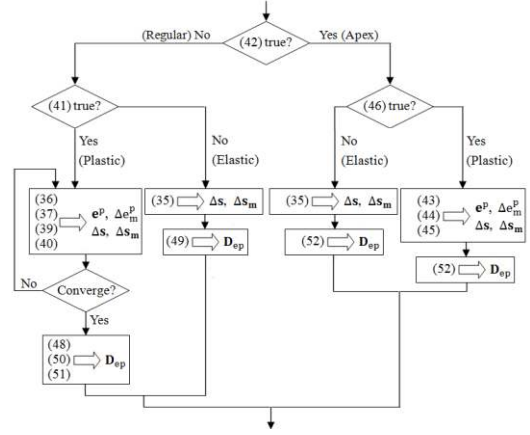


Figure 3 Constitutive integration algorithm

2) Structure

The algorithm for a structure in one iteration is shown in Figure 4.

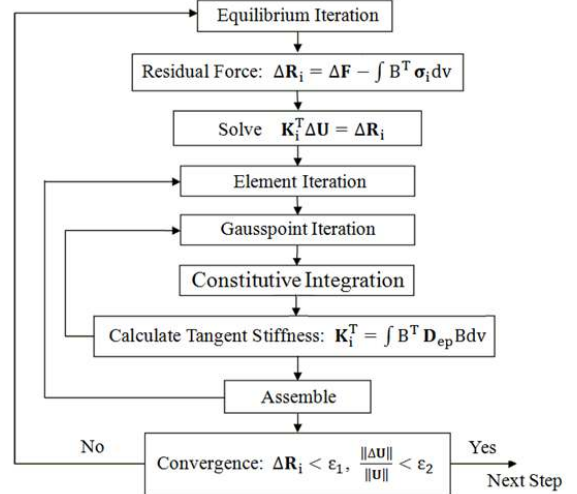


Figure 4 Algorithm for structure in one step

V. Simulation examples

A. Compression/traction test

1) Numerical solution

Let us take a 4-node unit as an example under a uniform compression and traction condition. The aim of this example is to check the correctness of integrating constitutive equations on one stress point, i.e., Gauss point. The characteristics are: $E = 0.5 \times 10^5$ MPa, $\nu = 0.33$, $c = 30$ MPa, $k_d = 1.01566$, $\phi = 40^\circ$, $\theta = 40^\circ$. Because the D-P model is an ideal plastic model, displacement boundary conditions are applied to make the results converge. The model is shown in Figure 5.

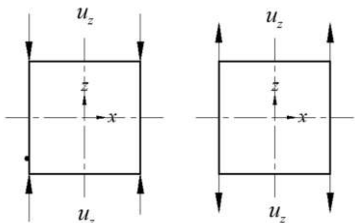


Figure 5 Compression/traction unit

On the coordinate of $\|s\| - s_m$, the D-P model constitutive curve is obtained and plotted in Figure 6.

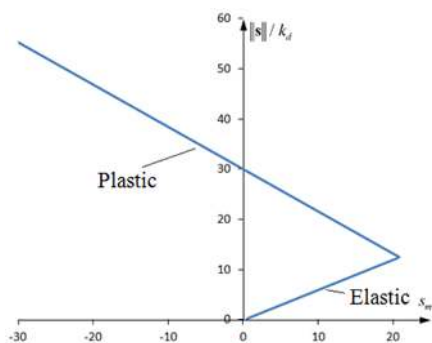


Figure 6 D-P model $\|s\| - s_m$ curve

As compared with Figure 1, an excellent match of D-P model constitutive curve can be seen by simulation and analysis. With different dilatancy angles, i.e. $\theta = \phi = 40^\circ$, $\theta = \phi / 2 = 20^\circ$, $\theta = \phi / 4 = 10^\circ$ and $\theta = 0^\circ$, we can simulate four curves under compression and traction respectively as follows,

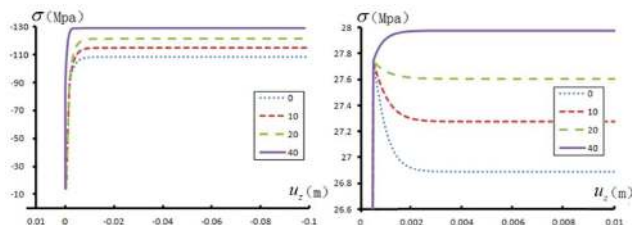


Figure 7 $u_z - \sigma$ curve of compression/traction

We observe from Figure 7 that the limit stress increases with the increase of dilatancy angle. The $u_z - \sigma$ curve

conforms to the ideal plastic. When the dilatancy angle does not equal to the internal friction, softening phenomenon appears at the beginning of the loading in traction case. The greater gap between dilatancy angle and internal friction is, the more obvious softening phenomenon will be.

2) Analytical solution

For this simple example, an analytical limit stress is available and given by [10]

$$\sigma = \frac{c}{\tan \phi} \frac{2}{1 \pm (2 - \tau \xi / \sqrt{3 \xi (2 - \tau^2 \xi)})} \quad (53)$$

$$\text{with } \tau = \tan \theta / \tan \phi \text{ and } \xi = 1 / 3 \cdot k_d^2 \tan^2 \phi \quad (54)$$

where “-” stands for compression, “+” stands for traction. The accuracy of the simulation is verified by comparing numerical solution and analytical solution in Table 1.

Table 1 Numerical solution and analytical solution

θ ($^\circ$)	Analytical solution (MPa)		Numerical solution (MPa)	
	compression	traction	compression	traction
40	-128.669	27.97837	-128.669	27.9784
20	-121.094	27.60294	-121.094	27.6029
10	-115.046	27.27608	-115.046	27.2761
0	-108.439	26.88765	-108.439	26.8876

B. Plane strain problem

The second example is devoted to apply the D-P model to a structure under plane strain conditions. The material characteristics are the same as in the above example. The geometry parameter and the finite element mesh are shown in Figure 8. The mesh involves 128 rectangle elements.

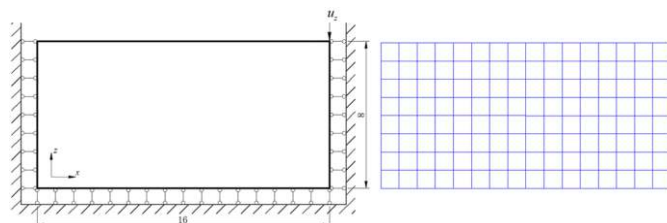


Figure 8 Geometry parameter and mesh

Assuming that the soil is weightless, given a displacement of $u_z = -0.001m$ on the right upper corner, we can simulate u_z , σ_z and ε_z^p for $\theta = \phi = 40^\circ$. The result is displayed by the in-house post-processing software FERView.

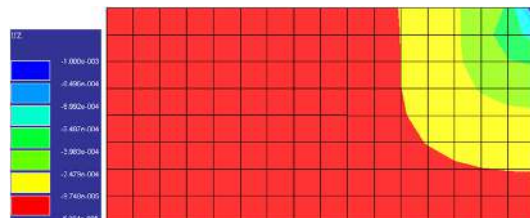


Figure 9 Displacement field

The displacement fields (Figure 9) show the continuity of the deformation. Due to the compressibility of the soil, an obvious phenomenon of compression would appear when enlarging the magnification factor.

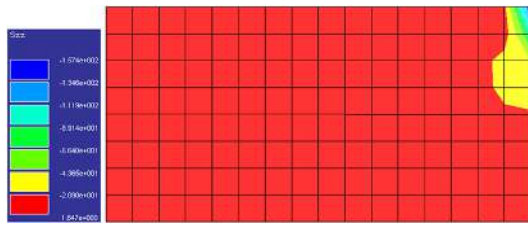


Figure 10 Stress fields

The maximum stress in Figure 10 is greater than the limit stress in the first example. The reason can be explained by the ferruling phenomenon under the three-side fixed constraints. The compressive stress is mainly concentrated in the areas of displacement constraints.

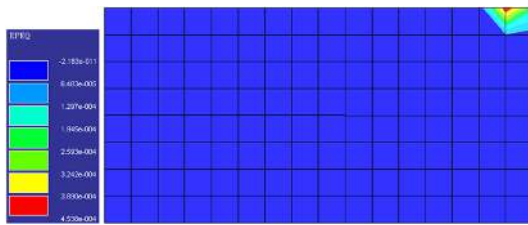


Figure 11 Plastic strain fields

As shown in Figure 11, the plastic zones can be clearly illustrated. In addition, it is only in the places where large shape changes that exists the zones in plastic stage. Other zones are still in elasticity.

Besides, more results under different dilatancy angles can be obtained as indicated in Table 2.

Table 2 Results of different dilatancy angles

θ (°)	Displacement (m)		Stress (MPa)		Plastic strain	
	max	min	max	min	max	min
40	5.294e-5	-0.001	1.847	-157.4	4.533e-4	≈0
20	4.936e-5	-0.001	1.902	-155.5	6.131e-4	≈0
0	4.438e-5	-0.001	1.981	-153.5	8.363e-4	≈0

According to Table 2, a rule can be summarized: the maximum stress at the loading direction enlarges with the increase of the dilatancy angle. The plastic zones are also expanding with the dilatancy angle. The simulation results almost match with that of ANSYS code. The rationality of the bi-potential theory and the feasibility of its algorithm can thus be proved.

VI. Conclusion

The bi-potential of the D-P model for non-associated soil materials is established. It has been shown that the bi-potential theory allows expressing better the flow rule of non-associated materials. By the finite element discretization, a constitutive integration method for the D-P model is obtained. Numerical solutions are validated as compared with theoretical ones. Through the simulation of the plane strain problem, the

rationality of the bi-potential theory and the feasibility of its algorithm are well verified. To conclude, the bi-potential theory in dealing with set problems shows its great potential in future research. Considering large deformation and frictional contact interfaces, this approach can be extended to deal with a rigid wall standing on the ground. The fields of the soils under the influence of the rigid wall could be analyzed. What's more, the simulation of the pile driving, a still complicated problem, could be analyzed when considering dynamic effects.

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