III. INTERFACE MODELLING UNDER A MONOTONIC LOADING

III.1. MODEL DISCRIPTION

The constitutive model used in this study, is an elastic model with a failure criterion based on the Mohr-Coulomb failure criterion (elastic-perfectly plastic model). The model had showed that it was insufficient to take into account all the phenomena of the interfaces (see Figure 27), including the phenomena of dilatancy contractancy, non-linearity in a CNL test and the degradation of the normal stress in a CNV test.

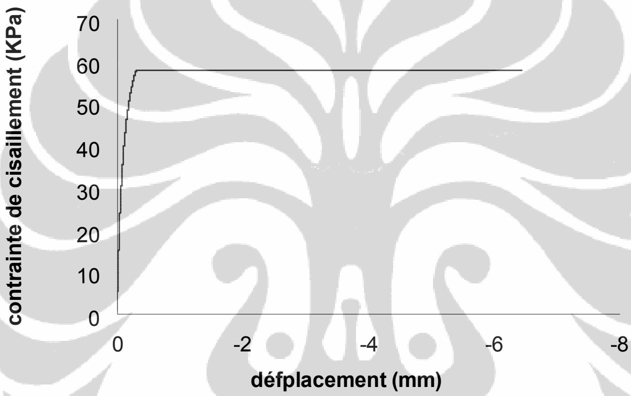

Figure 27. Stress- deformation relation with the the elastic-perfectly plastic model during a CNL test (FLAC)

In this study, it is suggested some internal variables and parameters that can reproduce some aspects of behaviour interface explicitly described in the preceding paragraphs, namely non-linear shear stress curve (non-linear elastic model), the dilatancy and the degradation of shear resistancy. All parameters and variables proposed respect the concepts and assumptions include:

- The Mohr Coulomb criterion.
- The concept of the large deformations.
- The degradation of shear stiffness due to hardening.
- The influence of the effective normal stress and density initial to the shear stiffness module of the soil.
- The state caracteristics who define the changement in the behaviour of interface Contracting expands.

- The similarity of the interface behaviour between rough interface with dense sand and sand (Boulon and Nova, 1990).

The study will focus on the behaviour of the interface without taking into account the increment of normal stress. The modeling is based on a direct shear test at normal stress constant (CNL).

III.1.1. Non-linear elastic model

As proposed by Riyono and Vincens (2007), there is a model that could reproduce the nonlinearity and can be injected into the basic constitutive model:

$$K_s = K_{s\max}\left(F_{NL}\right) \qquad (3.1.1.1)$$

Where F_{NL} is the function who introducing a non-linearity in the model. It is composed as follows:

$$F_{NL} = \frac{K_s}{K_{s\max}} = \left(1 - \frac{\tau}{\tau_y}\right)^a \exp\left(-\frac{\tau}{\tau_y}\right) \qquad (3.1.1.2)$$

$$\tau_y = \sigma_n \tan\phi_{max} \qquad (3.1.1.3)$$

With: K_s = Actual shear stiffness module (kPa/mm)

K_{smax} = Initial maximum shear stiffness module (kPa/mm)

a = Model parameter

ϕ_{max} = Friction angle at the maximum shear resistance state (at failure)

The following law of Hertz, just like for soil, defines the maximum shear stiffness module:

$$K_{s\max} = K_{s0}\left[\frac{\sigma_n}{\sigma_{ref}}\right]^n \qquad (3.1.1.4)$$

Where: n = Model parameter

σ_{ref} = Reference confinement (100 kPa)

K_{s0} = Initial shear stiffness module (kPa/mm)

III.1.2. Failure criterium

The model proposed in this study is a modified Mohr-Coulomb model, this modification can take into account the shear stress softening on the shear stress-deformation relation. This model is therefore presented in a form below:

$$f(T,\phi_m,\varepsilon_s) = \|T_T\| - T_N \tan f(\phi_m) = 0 \qquad (3.1.2.1)$$

Where T represent stress ; ϕ_m, friction angle along the tests ; ε_s is shear deformation and $f(\phi_m)$ is the softening model. The details of this equation is given in the next section.

III.1.3. Shear stress softening model

The behaviour of the interface of a dense material at a shear test, shows a pattern of deterioration of the system's ability to resist shear: a phenomenon that is called shear stress softening (see Figure 11 or 14). Physically, this means that the maximum degree of friction with an interface with a dense sand, is higher than the at large strains.

The shear stress softening may be reflected in the friction angle, clearly expressed in the following equation of shear-normal stress relation:

$$\tau = \sigma_n \tan f(\phi) \qquad (3.1.3.1)$$

Where $f(\phi)$ is the friction angle function for interface.

The constitutive model for the interface provided by FLAC (See FLAC modeling for more detail on this topic) does not include sufficient parameters to reproduce this phenomenon.

Several models have been proposed to address this issue, one of them is the DSC model (Disturbed State Concept) by Desai and Ma (1992). Their model is based on the idea that the actual behaviour observed in a test may be formed on the basis of two reference behaviour and a few benchmarks (see Figure 28). One of the behaviour of reference is that of a intact test, ie. the response of the material with its original initial condition which are constant, and the other is the limit at large strains.

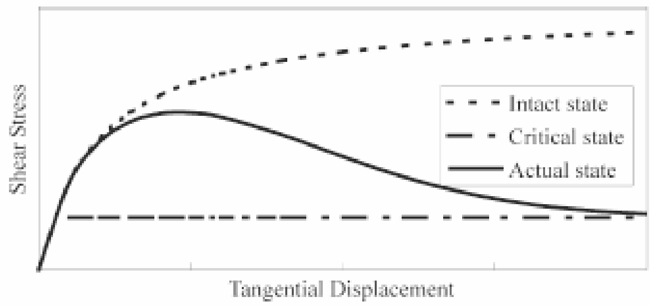

Figure 28. The DSC concept for a drained test.

According behaviour intact and states chosen benchmarks, we can take into account various aspects in the modeling of interfaces, as an element that disrupts the system. For example: friction, anisotropy or radoucissement.

The model proposed in this report for radoucissement model is based on the idea of the model described above. Taking the response of the model as non-linear elastoplastic behaviour intact and taking up the state and the state of deformation as points of reference, a function that expresses the degradation of the friction angle due to radoucissement can be formulated. This equation satisfies the following conditions:

At maximum state → The angle of friction is equal to the maximum angle.

$$f(\phi) = \phi_{\max} \text{ for } u_s = u_{s_{\max}}$$

At large-strain state → The friction angle equals the angle of friction at large deformation.

$$f(\phi) = \phi_{res}$$

This function is presented as follows:

$$\tan f(\phi) = \tan\phi_{\max} + \langle R \rangle * (\tan\phi_{res} - \tan\phi_{\max}) \qquad (3.1.3.2)$$

Where : $f(\phi)$ = Friction angle

$\phi_{\max}$ = Friction angle at the maximum state

ϕ_{res} = Friction angle at the large-strain state

R is the shear stress softening model proposed. R is 0 since the beginning of loading up to the state maximum, and then increase to 1 until it reached the state of deformation (see Figure 29). It is formulated as follows

$$\langle R \rangle = 1 - \exp(-a_2 * \varepsilon_s^{p^b}) \qquad (3.1.3.3)$$

$$\varepsilon_s^p = \varepsilon_s - \varepsilon_s^e \qquad (3.1.3.4)$$

Where: a_2 , b = The parameters of the model

ε_s^p and ε_s^s are the components of deformation which correspond to the elastic and plastic deformations. They can be calculated with the following equations:

$$\varepsilon_s^e = \frac{\tau}{k_s} \qquad (3.1.3.5)$$

$$\varepsilon_s = \frac{u_s}{l} \qquad (3.1.3.6)$$

l is the thickness of interface ($l = 5D_{50}$ for a smooth interface and $= 10D_{50}$ for a rough interface); u_s is the displacement tangential. Note that the interface width l is not a parameter of the model.

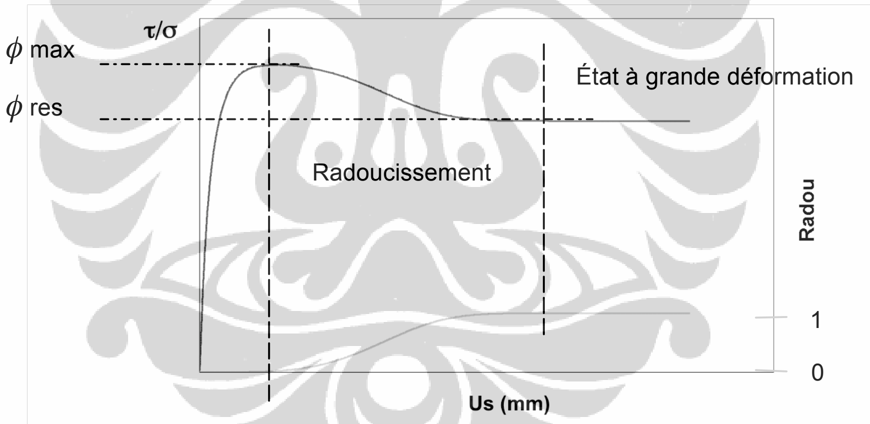

Figure 29. Modelisation details of stress softening model

III.1.4. Dilatancy model

The dilantion and contraction are two basic phenomena of displacement cure that are due to re-arrangement of soil particles. As mentioned in Chapter II, these phenomens depend on the initial density of the soil.

In the case of dense sand, the first observation can be made on the displacement curve is that the interface is contracted until the state characteristic before being followed by a dilatancy. Boundary conditions basic to reproduce this phenomenon can be inferred from these observations. The boundary conditions are:

As long as $\tau / \sigma_n - M < 0$ The system contract

if $\tau / \sigma_n - M = 0$ the system reaches the caracteristics state

if $\tau / \sigma_n - M > 0$ the system dilate

M is the coefficient of friction at the state characteristic.

$$M = \tan \phi_{car} = \tau_{car} / \sigma_{n_{car}} \qquad (3.1.4.1)$$

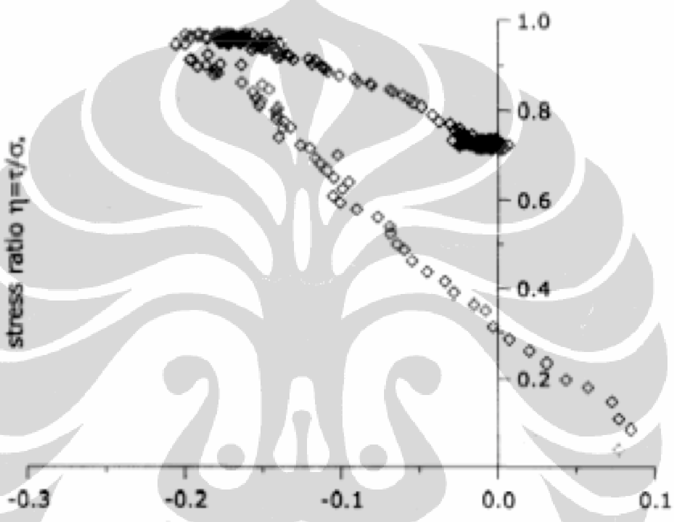

Figure 30. Dilatancy flow rule (Ghionna et Mortara, 2002)

It further notes the phenomenon of decline in the dilatancy to a large-strain level at which the interface moves in shear, without the slightest normal movement. Figure 30 shows the evolution of the stress ration on the degree of dilatancy. Through this relationship, it may also be noted that the magnitude of dilatancy decreases almost linearly with the ratio requirements.

The model proposed in this study is based on these observations and takes the following form:

$$\frac{\Delta u_n^{irr}}{|\Delta u_s|} = \left(\frac{\tau}{\sigma_n} - \tan \phi_{car} \right) * \beta * \alpha_R \qquad (3.1.4.2)$$

Where: Δu_n^{irr} = Irreversibel normal displacement increment (m)

Δu_s = Tangentiel / shear displacement increment (m)

τ = Shear stress (KPa)

σ_n = Normal stress (KPa)

ϕ_{car} = Friction angle at the caracteristics state

β = Model parameter

α_R is a mathematical function to translate the loss of dilatancy from the maximum resistance state of the interface to the large strain state (second phase displacement curve). It can be defined in the same manner as for the function of <R> softening by taking inverses boundary conditions:

$$\langle \alpha_R \rangle = 1 \qquad \text{as long as} \qquad \tau/\sigma_n - M < 0$$

$$\langle \alpha_R \rangle = 0 \qquad \text{if} \qquad \tau/\sigma_n - M > 0$$

α_R can be defined as:

$$\alpha_R = 1 - \langle R \rangle = \left(1 - \frac{\tan\phi_m - \tan\phi_{max}}{\tan\phi_{res} - \tan\phi_{max}} \right) \qquad (3.1.4.3)$$

Where ϕ_m = Current friction angle

ϕ_{max} = Friction angle at the maximum resistance state

ϕ_{res} = Friction angle at the large-strain state

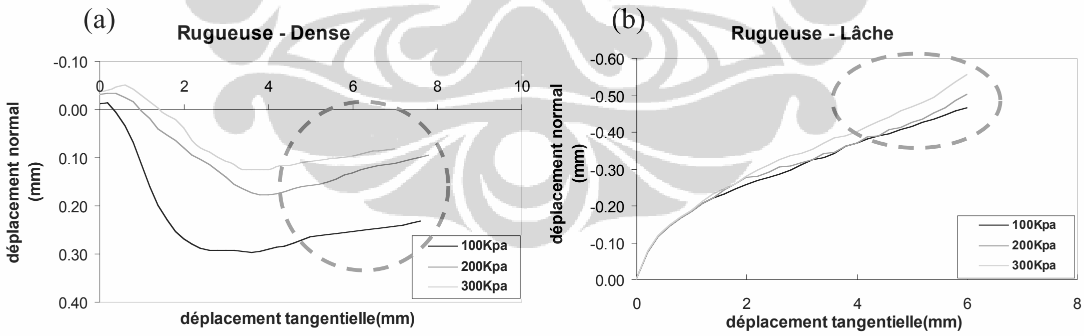

Figure 31. Second phase of contractancy on the displacement curve for a rough interface with: a) dense sand (ID=90%) ; b) loose sand (ID=15%). [Shahrour et Rezaie 1997]

This equation is used to reproduce the behaviour of the displacement curve, which is injected directly into the model. It is not quite a correct method from the mechanical point of view, but it can still be used as a first approach to better understand the dilatant-contractant behaviour of the interface. A more accurate model for a monotone solicitation was studied by Rinaldy (2008).

According to some experimental results, a third phase appears on the displacement curve, often called the second contraction phase (see Figure 31). It will not be taken into account in modeling.

III.2. IDENTIFICATION OF THE MODEL PARAMETERS

III.2.1. Elastics parameters

Four elastic parameters are proposed in this model: k_n, k_s, n and a. k_n and k_s are the normal and tangential stiffness modules of the interface. Figure 32 illustrates the mechanism of these modules.

The tangential stiffness k_s, can be deduced from a compression test interface or indirectly from a test interface shear produced under zero normal displacement zero (CNV). The normal stiffness k_n can be inferred from a test interface shear CNL. Their values may be determined by the following relations:

$$d\sigma_n = k_n \cdot du_n^e \qquad (3.2.1.1)$$

$$d\sigma_s = k_s \cdot du_s^e \qquad (3.2.1.2)$$

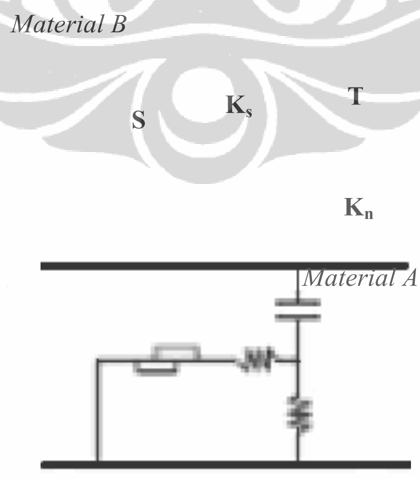

Figure 32. Interface modelisation

The parameter a is used to model the deterioration of the tangential stiffness, ie non-linearity observed at the shear stress curve. More value, the greater the radius of curvature is large and the ultimate status will be achieved for values of u ¬ s large (see Figure 33).

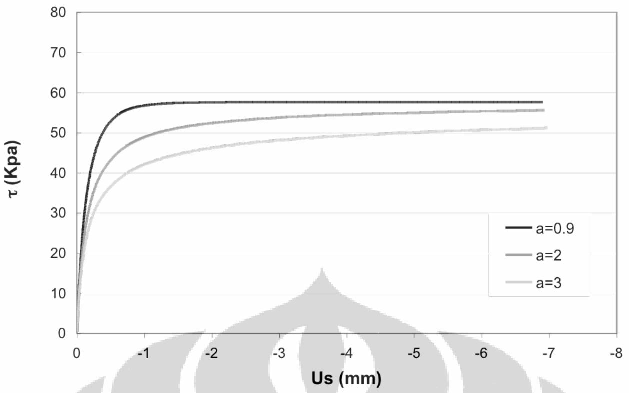

Figure 33. Influence of *a* on the shear stress-normal deplacement

The fourth parameter *n*, is in fact a parameter of the law of Hertz. In this study, this will be manipulated to control the degree of normalization of the initial normal stress. Figures 34 and 35 respectively show the influence of the magnitude of the latter on the shear stress curve and on the displacement curve of the interface. Both figures prouve well the advatages of using the parameter n: in fact he ran the influence of the magnitude of normal stress on each interface, by standardizing it to a reference normal stress of 100 kPa. That is why this parameter does not influence the test at 100 kPa

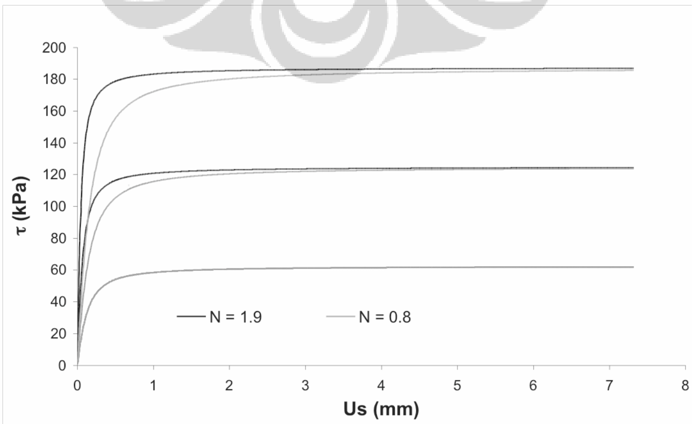

Figure 34. Influence of *n* on the shear stress curve

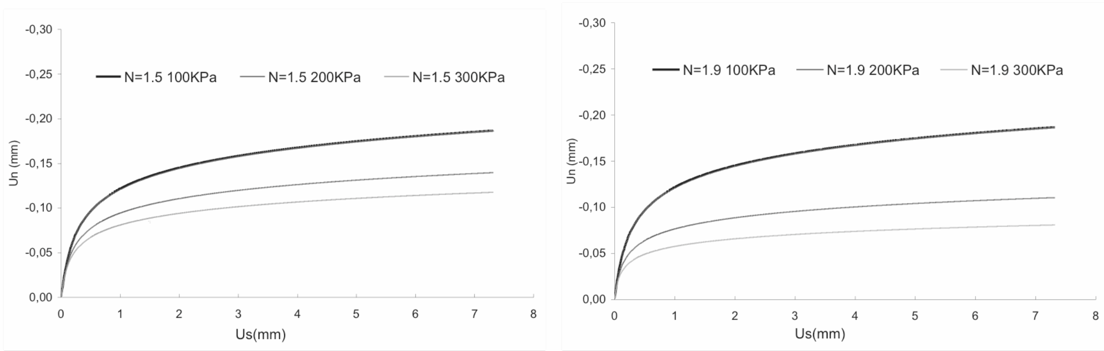

Figure 35. Influence of *n* on the normal deplacement curve for a CNL test simulation on a rough interface with a loose sand (*ID*=15%)

III.2.2. The differents states of references parameters for an interface

The parameters of the various references states are the angles of friction at the maximum state ($\phi_{\max}$), characteristic state (ϕ_{car}) and the large-strain state (ϕ_{res}). As explicitly defined in section II.1, the friction angles of each state can be inferred from a direct shear test at a constant normal stress. They correspond to the peak of the shear stress curve, the change of behaviour of the displacement curve and a constant plate at large-strain state.

The parameters used in this study are deducted from the tests carried out by Shahrour and Rezaie (1997). Because of inevitable errors and inaccuracies in measurement during tests, it is sometimes difficult to identify the parameters, especially for a test on dense sand. The results of the CNL test for a rough interface with dense sand for example, they seem abnormal cause they didn't respect the hypothesis of augmentation of the stress. From the shear stress curve with the results for tests of 100, 200 and 300 kPa, the test with 200 kPa seems incoherent (see Figure 14 and appendix A). For the rest of the simulation, the experimental results of the interface with a rough sand dense σ_n = 200Kpa will not be used.

In this study, for simulations on dense sands, average values will be taken for the parameters, ϕ_{car} ,$\phi_{\max}$ and ϕ_{res}. However, for loose sand, these parameters will be deducted directly from the experimental curves.

Figure 36 shows an example of identifying the friction angle of maximum resistance state for a rough interface with dense sand. The vertical lines show the maximum resistance states for various normal stresses imposed. The friction angle for each test varies from 40° to 38.6° ($\tan\phi = 0.839$ to 0.798 for σ_n=100kPa and 300 kPa).

The friction angle that will be used for the simulation of a rough interface with dense sand is the maximum value of them, 40°.

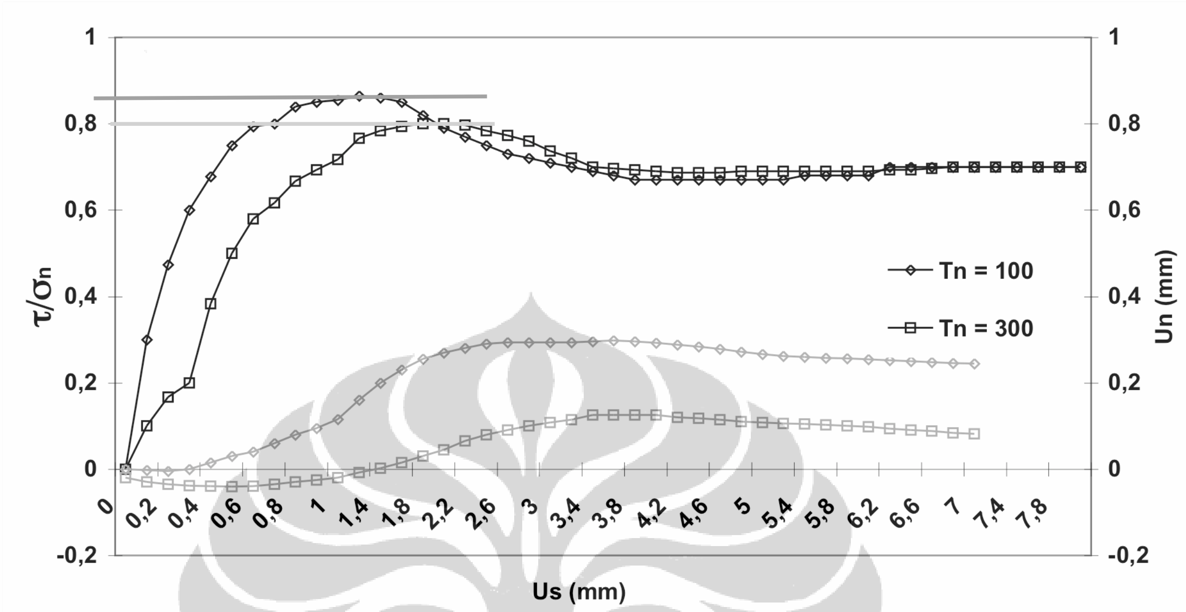

Figure 36. Identification of the maximum shear resistance state parameter

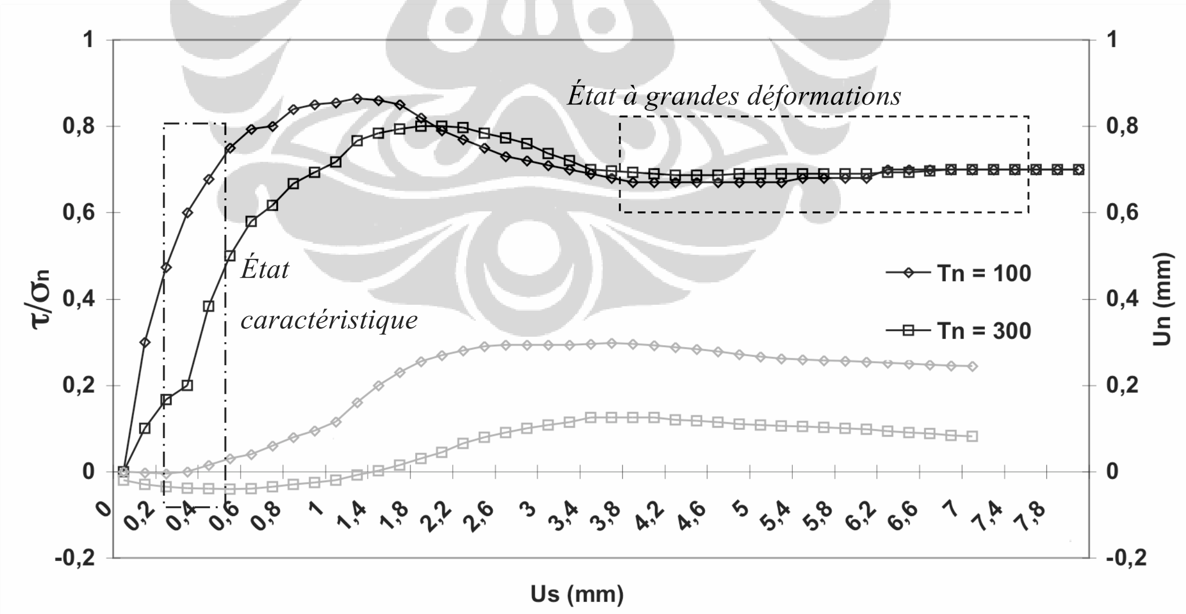

Figure 37. Identification characteristics and grand deformation state parameters

Figure 37 presents the identification of two other parameters for the same tests. The value of the friction angle at large-strains for each normal stress imposed (σ_n) ranged from 33 to 35 degrees. The identification of the characteristic angle of friction is more difficult since the results for each test gives values ranging from 22 to 30 degrees ($\tan\phi = 0.4$ to 0.57 for σ_n = 100 kPa and 300 kPa). To assess the value of that angle, several simulations were conducted by different values of friction angle to find the one that fit the most to the experimental results.

Table 1.   Friction angle's interval

	$\phi_{\max}$	ϕ_{car}	ϕ_{res}
Interface : Rough Sable : Dense	40°	20 – 29°	30 – 33°
Interface : Rough Sable : Loose	31.8 – 32.2°	31.8 – 32.2°	30 – 33°
Interface : Smooth Sable : Dense	± 30°	29 – 30°	28.8 – 29.6°
Interface : Smooth Sable : Loose	22.8 – 25.2°	22.8 – 25.2°	22.8 – 25.2°

Table 1 summarizes all intervals of friction angle from each state according to different types of interfaces and soil used in the experiments by Shahrour and Rezaie (1997).

III.2.3. Stress-softening parameters

Two parameters, a_2 and b were proposed to control the degree of the softening model. The first control the speed of softening. Figure 38 shows the shear stress curve obtained from the shear softening model for a dense material and different values of a_2. It shows that the greater the value a_2, the interface reaches more quickly the residual state.

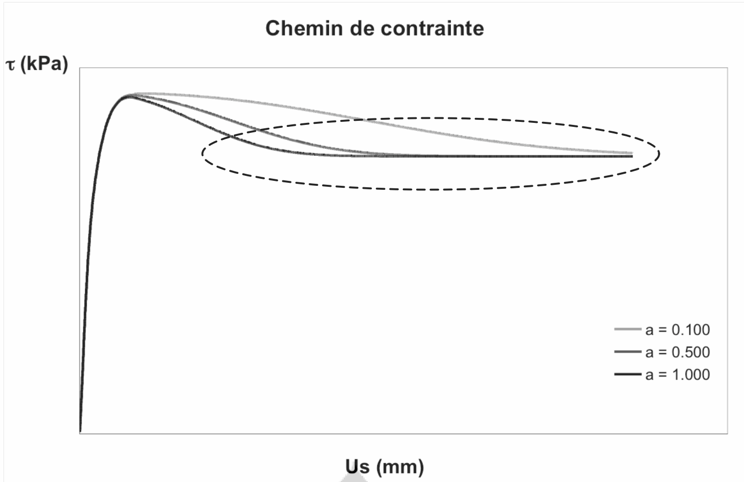

Figure 38. Influence of a_2 on the shear stress-deplacement relation (shear stress curve)

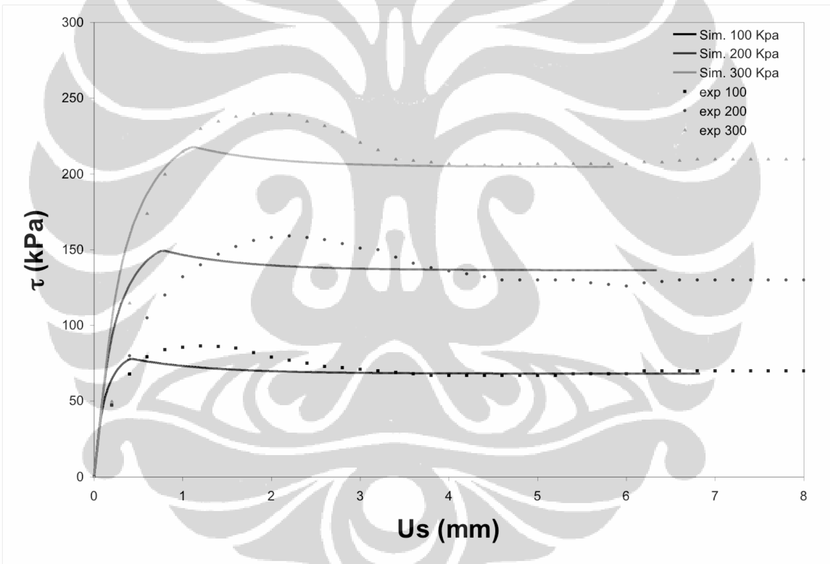

Figure 39. Shear stress curve of the proposed model, with only one parameter, a_2 for a rough interface with dense sand.

A second parameter, *b* can be added to refine the shear stress softening model. Figure 39 presents the results obtained with the shear softening model with only one parameter a_2. It shows that it lack indeed another parameter to reproduce the interface behaviour at smaller deformation. The parameter *b* is introduced to control and reproduce the behaviour at this state. The influence of the magnitude of this parameter is illustrated in Figure 40. The greater this value is, the slower the interface reach its maximum state.

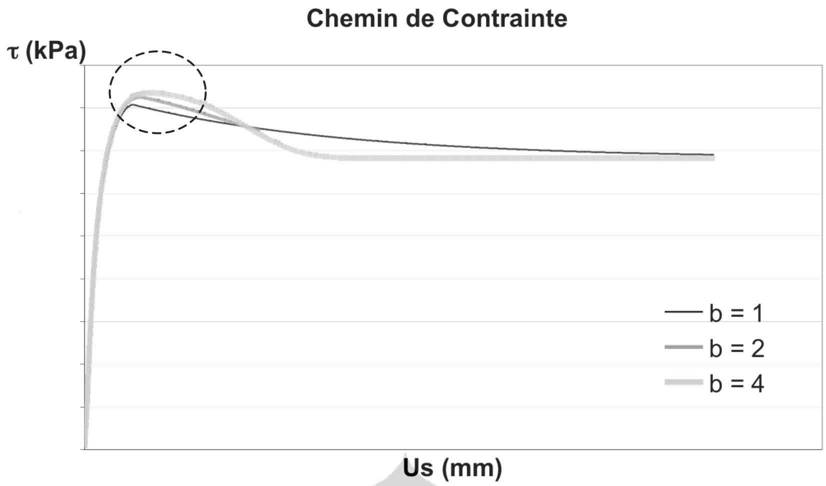

Figure 40. Influence of *b* on the shear stress-deplacement curve.

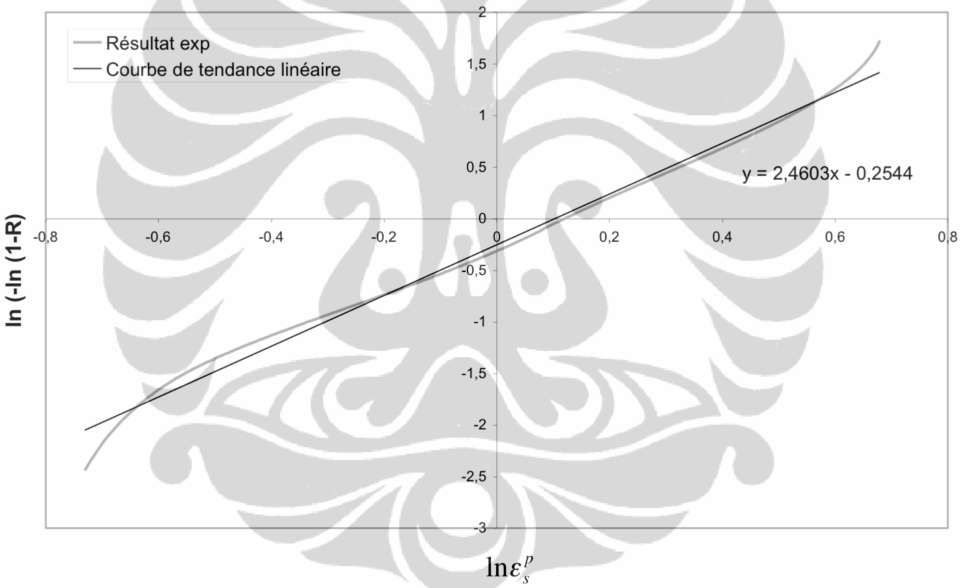

Figure 41. Example of calibration of a_2 and *b* for a rough interface

Some first values of these parameters can be deducted from the results of a CNL test. Figure 41 shows an example of calibration of these parameters in the case of a rough interface. It introduces the relationship $\ln\left[-\ln\left(1-\langle R\rangle\right)\right]$ and ε_s^p as:

$$\ln\left[-\ln\left(1-\langle R\rangle\right)\right] = \ln a + b \ln \varepsilon_s^p \qquad (3.2.3.1)$$

III.2.4. Dilatancy model parameters

The model parameter that controls the contractancy-dilatancy behaviour of interface proposed is β (a side of ϕ_{car}). It determines the amplitude of the contraction and dilatation.

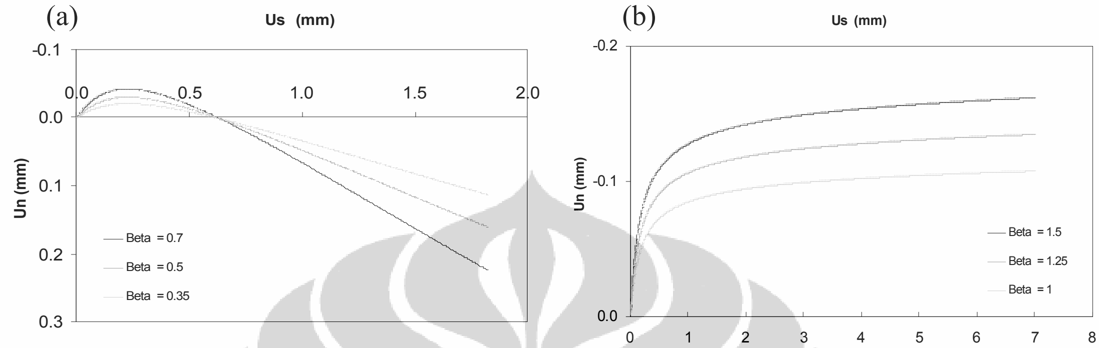

Figure 42. Influence of β for an interface: (a) with dense sand (*ID*=90%) ; (b) with loose sand (*ID*=15%)

Figure 42 shows the normal displacement curve according to the tangential displacement in different values of β, for a dense sand and loose sand. In the first case where the contraction usually occurs at the beginning of loading followed by dilatation, the value of β influence both the amplitude and the slope of the curve in Figure 42.a. In contrast to loose sand, which usually suffer only contraction in each type of interface, the value of β determines the final value of the permanent plate at large-strains states.

III.3. PARTIAL CONCLUSION

The main objectives of the modelling in this study were to translate and represent the general behaviour of the interface during a drained shear test (CNL) based on the Mohr-Coulomb law. We saw that it was important to take into account the increase in resistance as a function of confinement and the shear stress softening and contractancy-dilatancy behaviour for dense sand.

In fact all the parameters are coupled with each other. Although in this chapter, the parameters have been presented and deducted individually, it is virtually impossible to determine a parameter properly without taking into account the influence of others. Apart from β, the parameter of dilatancy model, which has influence only on the magnitude of the displacement curve. Several tests with different sets of parameters have to be made to derive a model that gives results, which is consistent with the experimental ones.