*CONSTRAINED_SOIL_PILE

Purpose: Define penalty-based coupling between 1D beam elements and 3D solid elements. The beam elements must not share nodes with the solid elements, and the beam element mesh does not have to align with the solid element mesh. The functionality is similar to *CONSTRAINED_BEAM_IN_SOLID, except that *CONSTRAINED_SOIL_PILE is specific to geotechnical applications, such as piles in soil or anchors in rock. For general applications in which beam elements must be coupled with solids (such as reinforcement bars in concrete), *CONSTRAINED_BEAM_IN_SOLID is recommended due to its simpler input. See the general modeling requirements for *CONSTRAINED_SOIL_PILE in Remarks 1 through 4.

The data cards described below specify the nonlinear coupling characteristics, expressing the resisting stress on the outer surface of the pile as a function of displacement of the pile relative to the soil. Movement in the axial (sliding) direction has a different coupling characteristic from movement perpendicular to the axis of the pile. In geotechnical terminology, the perpendicular coupling characteristics are sometimes described as “P-y springs” while the axial characteristics are described as “P-z springs”. Additionally, a coupling characteristic is required for axial movement of the base of the pile, sometimes referred to as the “end-bearing” or the “toe” of the pile. Thus, the overall coupling depends on a set of three nonlinear coupling characteristics (Base, Axial and Perpendicular).

Where piles pass through layers of soils with different material properties, different coupling properties may be appropriate for each soil layer. To model this, include one *CONSTRAINED_SOIL_PILE keyword containing multiple sets of coupling properties. Each set of coupling properties is associated with a particular soil part ID or part set ID. LS-DYNA will then select the coupling properties for each node of the pile according to the part ID of the soil element within which that pile node is situated. LS-DYNA will automatically find the node at the free end of each pile for allocation of Base coupling properties (see description of LOCAL below for which free end will be taken as the Base).

OPTION1 specifies the format in which the coupling properties are defined on Cards 3 through 6. Available options are:

<BLANK>

CONSTANTS

CURVES

Selecting CURVES allows you to specify the properties with load curves while CONSTANTS allows you to specify the coupling with constant values. The input for the CURVES option is simpler than that of the CONSTANTS option, but the CONSTANTS option reduces the need to create load curves. If *OPTION1* is unset (<BLANK>), then the input is the same as for CONSTANTS, except that Card 2 is omitted. Card 2 allows you to add damping to the axial coupling shear stress and to pick which side of the pile is the Base. We recommend using CONSTANTS or CURVES for *OPTION1* instead of not setting it. <BLANK> is included solely for backwards compatibility.

OPTION2 specifies whether the soil parts to which the coupling properties apply are defined by part ID (see *PART) or by part set ID (see *SET_PART). Available options are:

<BLANK>

SET

If unset (<BLANK>), part IDs are assumed.

Card Summary:

Card Sets. Include one of Cards 1 and 2 (unless *OPTION1* is unset) total. Then for each soil part/part set include one set of either Cards 3a through 6a or Cards 3b through 6b depending on *OPTION1*. Include as many sets as required to define the coupling properties for all the relevant soil layers. This input ends with the next keyword (“*”) card.

Card 1. This card is required.

PBSID	DIAM		PIDNS	PIDNB	ERROR	NRING	NRINGB

Card 2. This card is included unless *OPTION1* is unset (<BLANK>).

DAMP	LOCAL						

Card 3a. This card is included when *OPTION1* is set to CONSTANTS or not used (<BLANK>). Include as many sets of Card 3a through Card 6a as needed.

PID/PSID	ACU	BCU	LCCU	ASTIFFS	BSTIFFS	ASTIFFB	ZREF

Card 4a. This card is included when *OPTION1* is set to CONSTANTS or not used.

KBCON	KBCU	KBSX	KBSY	KBSZ	BSTFAC	BHYPER	BLC

Card 5a. This card is included when *OPTION1* is set to CONSTANTS or not used.

KVCON	KVCU	KVSX	KVSY	KVSZ	VSTFAC	VHYPER	VLC

Card 6a. This card is included when *OPTION1* is set to CONSTANTS or not used.

KHCON	KHCU	KHSX	KHSY	KHSZ	HSTFAC	HHYPER	HLC

Card 3b. This card is included when *OPTION1* is set to CURVES. Include as many sets of Card 3b through Card 6b as needed.

PID/PSID	ZREF						

Card 4b. This card is included when *OPTION1* is set to CURVES.

BLCZ	BLC	BLCSH	BLCSV				

Card 5b. This card is included when *OPTION1* is set to CURVES.

VLCZ	VLC	VLCSH	VLCSV				

Card 6b. This card is included when *OPTION1* is set to CURVES.

HLCZ	HLC	HLCSH	HLCSV	HLCFD			

Data Card Definitions:

Card 1	1	2	3	4	5	6	7	8
Variable	PBSID	DIAM	(blank)	PIDNS	PIDNB	ERROR	NRING	NRINGB
Type	I	F		I	I	I	I	I
Default	none	0.0		none	none	0	1	↓

VARIABLE	DESCRIPTION
PBSID	Part set ID containing beam elements for coupling (the piles). See Remarks 2 and 3.
DIAM	Pile diameter (optional). If zero or blank, the pile diameter will be taken automatically from the section properties of the beam element. See Remarks 3 and .
PIDNS	Part ID for coupling visualization elements. See Remarks 14 and 15.
PIDNB	Part ID for coupling visualization elements on base. See Remarks 14 and 15.

VARIABLE	DESCRIPTION
ERROR	Action taken if any coupling point is not constrained within a soil element: EQ.0: Stop with an error message. EQ.1: Warn and continue.
NRING	Number of coupling points around circumference at each pile node (see Remarks 11, 12 and 13): EQ.1: One coupling point coincident with pile node GT.1: NRING coupling points equally spaced around the circumference of the pile
NRINGB	Number of extra rings of coupling points on base, in addition to those around the pile circumference. By default, NRINGB is chosen automatically to distribute the base stress as uniformly as possible (see Remarks 11 and 12).

This card is included unless *OPTION1* is unset (<blank>).

Card 2	1	2	3	4	5	6	7	8
Variable	DAMP	LOCAL						
Type	F	I						
Default	0.0	1						

VARIABLE	DESCRIPTION
DAMP	Optional damping coefficient for Axial coupling (stress/velocity units). An additional axial coupling shear stress equal to DAMP times the axial velocity of the pile relative to the soil will be generated. See Remark 17.
LOCAL	Flag to identify which free end of a pile is treated as the Base: EQ.1: End with the most negative global *Z*-coordinate EQ.2: End which is Node 1 of the attached beam element topology

CONSTANTS General Coupling Properties Card. Include a set of Cards 3a through 6a for each soil part/part set when *OPTION1* is CONSTANTS or unset. Include as many sets as needed. See Remark 6.

Card 3a	1	2	3	4	5	6	7	8
Variable	PID/PSID	ACU	BCU	LCCU	ASTIFFS	BSTIFFS	ASTIFFB	ZREF
Type	I	F	F	I	F	F	F	F
Default	none	0.0	0.0	optional	0.0	0.0	0.0	0.0

VARIABLE	DESCRIPTION
PID/PSID	Part ID or part set ID (depending on *OPTION2*) containing solid elements for coupling (the soil). See Remarks 4 and 16.
ACU	Constant term in depth-dependence formula. Units of stress.
BCU	Coefficient on relative *Z*-coordinate in depth-dependence formula. Units of stress/length. Note that soil strengths (and therefore coupling properties) generally increase with depth, meaning they increase with an increasingly negative *Z*-coordinate. Therefore, this term is usually negative.
LCCU	Optional load curve ID giving stress (stress units) as a function of relative *Z*-coordinate (length units). If defined, LCCU overrides ACU and BCU. Note that "increasing depth" corresponds to "increasingly negative relative *Z*-coordinate".
ASTIFFS	Generic stiffness term. Units of stress / length.
BSTIFFS	Generic *Z*-coordinate-dependent stiffness term. Units of stress / length^2
ASTIFFB	Base stiffness. Units of stress / length.
ZREF	Reference *Z*-coordinate to calculate "relative *Z*-coordinate". See Remark 16.

CONSTANTS Base Coupling Properties Card. Include a set of Cards 3a through 6a for each soil part/part set when *OPTION1* is CONSTANTS or unset. See Remarks 6 and 8.

Card 4a	1	2	3	4	5	6	7	8
Variable	KBCON	KBCU	KBSX	KBSY	KBSZ	BSTFAC	BHYPER	BLC
Type	F	F	F	F	F	F	F	I
Default	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0

VARIABLE	DESCRIPTION
KBCON	Base coupling, constant term (stress units)
KBCU	Base coupling, coefficient for Cu (dimensionless)
KBSX	Base coupling, coefficient for effective global *X*-stress (dimensionless)
KBSY	Base coupling, coefficient for effective global *Y*-stress (dimensionless)
KBSZ	Base coupling, coefficient for effective global *Z*-stress (dimensionless)
BSTFAC	Base coupling, factor on elastic stiffness (dimensionless)
BHYPER	Base coupling, hyperbolic curve limit (dimensionless)
BLC	Base coupling, load curve ID for dimensionless factor on stress as a function of displacement

CONSTANTS Axial Coupling Properties Card. Include a set of Cards 3a through 6a for each soil part/part set when *OPTION1* is CONSTANTS or unset. See Remarks 6 and 9.

Card 5a	1	2	3	4	5	6	7	8
Variable	KVCON	KVCU	KVSX	KVSY	KVSZ	VSTFAC	VHYPER	VLC
Type	F	F	F	F	F	F	F	I
Default	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0

VARIABLE	DESCRIPTION
KVCON	Axial coupling, constant term (stress units)
KVCU	Axial coupling, coefficient for Cu (dimensionless)
KVSX	Axial coupling, coefficient for effective global *X*-stress (dimensionless)
KVSY	Axial coupling, coefficient for effective global *Y*-stress (dimensionless)
KVSZ	Axial coupling, coefficient for effective global *Z*-stress (dimensionless)
VSTFAC	Axial coupling, factor on elastic stiffness (dimensionless)
VHYPER	Axial coupling, hyperbolic curve limit (dimensionless)
VLC	Axial coupling, load curve ID for dimensionless factor on stress as a function of displacement

CONSTANTS Perpendicular Coupling Properties Card. Include a set of Cards 3a through 6a for each soil part/part set when *OPTION1* is CONSTANTS or unset. See Remarks 6 and 10.

Card 6a	1	2	3	4	5	6	7	8
Variable	KHCON	KHCU	KHSX	KHSY	KHSZ	HSTFAC	HHYPER	HLC
Type	F	F	F	F	F	F	F	I
Default	0.0	0.0	0.0	0.0	0.0	1.0	0.0	none

VARIABLE	DESCRIPTION
KHCON	Perpendicular coupling, constant term (stress units)
KHCU	Perpendicular coupling, coefficient for Cu (dimensionless)
KHSX	Perpendicular coupling, coefficient for effective global *X*-stress (dimensionless)
KHSY	Perpendicular coupling, coefficient for effective global *Y*-stress (dimensionless)
KHSZ	Perpendicular coupling, coefficient for effective global *Z*-stress (dimensionless)
HSTFAC	Perpendicular coupling, factor on elastic stiffness (dimensionless)
HHYPER	Perpendicular coupling, hyperbolic curve limit (dimensionless)
HLC	Perpendicular coupling, load curve ID for dimensionless factor on stress as a function of displacement

CURVES General Coupling Properties Card. Include a set of Cards 3b through 6b for each soil part/part set when *OPTION1* is CURVES. Include as many sets as needed.

Card 3b	1	2	3	4	5	6	7	8
Variable	PID/PSID	ZREF						
Type	I	F						
Default	none	0.0						

VARIABLE	DESCRIPTION
PID/PSID	Part ID or part set ID (depending on *OPTION2*) containing solid elements for coupling (the soil). See Remarks 4 and 16.
ZREF	Reference *Z*-coordinate, used in calculation of "relative *z*-coordinate". For example, ZREF may be located at the soil surface. See Remarks 7 and 16.

CURVES Base Coupling Properties Card. Include a set of Cards 3b through 6b for each soil part/part set when *OPTION1* is CURVES. See Remarks 7 and 8.

Card 4b	1	2	3	4	5	6	7	8
Variable	BLCZ	BLC	BLCSH	BLCSV				
Type	I	I	I	I				
Default	0	0	optional	optional				

VARIABLE	DESCRIPTION
BLCZ	For base coupling, load curve ID defining ultimate strength (stress units) as a function of relative *Z*-coordinate (length units)
BLC	For base coupling, load curve ID containing normalized mobilization curve: dimensionless factor on stress as a function of displacement
BLCSH	For base coupling, optional load curve ID containing coefficient for effective horizontal stress (dimensionless) as a function of

VARIABLE	DESCRIPTION
	relative Z-coordinate
BLCSV	For base coupling, optional load curve ID containing coefficient for effective vertical stress (dimensionless) as a function of relative Z-coordinate

CURVES Axial Coupling Properties Card. Include a set of Cards 3b through 6b for each soil part/part set when *OPTION1* is CURVES. See Remarks 7 and 9.

Card 5b	1	2	3	4	5	6	7	8
Variable	VLCZ	VLC	VLCSH	VLCSV				
Type	I	I	I	I				
Default	0	0	optional	optional				

VARIABLE	DESCRIPTION
VLCZ	For axial coupling, load curve ID defining ultimate strength (stress units) as a function of relative Z-coordinate (length units)
VLC	For axial coupling, load curve ID containing normalized mobilization curve: dimensionless factor on stress as a function of displacement
VLCSH	For axial coupling, optional load curve ID containing coefficient for effective horizontal stress (dimensionless) as a function of relative Z-coordinate
VLCSV	For axial coupling, optional load curve ID containing coefficient for effective vertical stress (dimensionless) as a function of relative Z-coordinate

CURVES Perpendicular Coupling Properties Card. Include a set of Cards 3b through 6b for each soil part/part set when *OPTION1* is CURVES. See Remarks 7 and 10.

Card 6b	1	2	3	4	5	6	7	8
Variable	HLCZ	HLC	HLCSH	HLCSV	HLCFD			
Type	I	I	I	I	I			
Default	0	0	optional	optional	optional			

VARIABLE	DESCRIPTION
HLCZ	For perpendicular coupling, load curve ID defining ultimate strength (stress units) as a function of relative *Z*-coordinate (length units)
HLC	For perpendicular coupling, load curve ID containing normalized mobilization curve: dimensionless factor on stress as a function of displacement
HLCSH	For perpendicular coupling, optional load curve ID containing coefficient for effective horizontal stress (dimensionless) as a function of relative *Z*-coordinate
HSCSV	For perpendicular coupling, optional load curve ID containing coefficient for effective vertical stress (dimensionless) as a function of relative *Z*-coordinate
HLCFD	For perpendicular coupling, optional load curve ID containing minimum frictional resistance during “post-hole” unload/reload (stress units) as a function of relative *Z*-coordinate

Remarks:

1. **General Requirements.** This keyword is available only for 3D models with the explicit solver. The model’s global *Z*-axis should be vertically upwards. If this is not the case, then it will not be possible to define depth-dependent coupling characteristics or to use the default of the LOCAL field for identifying the Base of piles.

2. **Mesh Requirements.** The beam elements must not share nodes with the solid elements. The beam element mesh does not have to align with the solid element mesh. Each pile must consist of contiguously meshed beam elements.

One *CONSTRAINED_SOIL_PILE definition can connect multiple piles to multiple soil layers. Although piles are generally aligned vertically, there is no requirement for this to be the case in the model. We recommend having consistent beam element local axes along a pile. Thus, neighboring elements should have Node 1 and Node 2 the same way around, such as Node 1 always being below Node 2.

3. **Beam Element Properties.** Beam elements must be ELFORM 1 or 2. *CONSTRAINED_SOIL_PILE treats the beams as if they have a solid circular cross-section with diameter DIAM. If DIAM is nonzero, the same value is used for all the beam elements included in the coupling. If DIAM is zero or blank, the diameter of the assumed circular cross-section is calculated for each beam element separately from the area of the cross-section given on the *SECTION card. The actual section shape may be non-circular and/or non-solid, but then the surface area of the pile assumed by *CONSTRAINED_SOIL_PILE will be different from the true surface area. This difference will result in the coupling stress being multiplied by an incorrect area to obtain the force. In these cases, DIAM should be defined such that $\pi \times \text{DIAM}$ equals the perimeter of the pile cross-section. For the beam elements, rigid material is not permitted and constraint-based features such as Nodal Rigid Bodies or SPC boundary conditions must not be present on their nodes.

4. **Solid Element Properties.** The solid elements must not have more than 8 nodes. There is no other restriction on element type or material type. Rigid material type is permitted, and there is no restriction regarding constraints or other features present on the nodes of the solids.

5. **Coupling Characteristics: General.** The coupling characteristics are defined in terms of stress on the outer surface of the pile as nonlinear functions of displacement of the pile relative to the soil. Coupling stress is calculated separately at each coupling point (coupling point locations are discussed in Remark 11). The response under monotonically increasing displacement is defined by a “backbone curve”, which is defined differently according to whether *OPTION1* is CONSTANTS (Remark 6) or CURVES (Remark 7). Backbone curves for all three coupling characteristics (Base, Axial and Perpendicular) follow the same pattern but with different input parameters. Unload/reload behavior is described in Remarks 8 through 10.

6. **Backbone Coupling Curves when *OPTION1* is CONSTANTS or Unset.** The coupling follows an elastic/plastic relation with an initial elastic stiffness and a yield stress. The elastic stiffnesses (stress/displacement) for Base, Axial and Perpendicular coupling (S_{Base}, S_{Ax} and S_{Perp}, respectively) are defined as follows:

$$S_{\text{Base}} = \text{ASTIFFB} \times \text{BSTFAC}$$

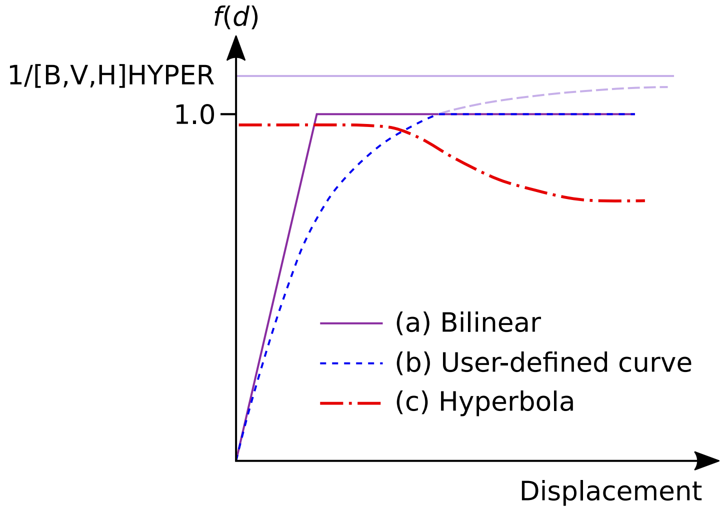

Figure 0-1. Forms of $f(d)$ available when *OPTION1* is CONSTANTS or unset.

$$S_{\mathrm{Ax}} = (\mathrm{ASTIFFB} + \mathrm{BSTIFF} \times z_r) \times \mathrm{VSTFAC}$$
$$S_{\mathrm{Perp}} = (\mathrm{ASTIFF} + \mathrm{BSTIFF} \times z_r) \times \mathrm{HSTFAC}$$

Here z_r is the relative Z-coordinate defined as $Z_0 - \mathrm{ZREF}$. Z_0 is the initial Z-coordinate of the pile node.

The yield stresses for Base, Axial and Perpendicular coupling ($\sigma_{Y,\,\mathrm{Base}}$, $\tau_{Y,\,\mathrm{Ax}}$ and $\sigma_{Y,\,\mathrm{Perp}}$, respectively) are defined as follows:

$$\sigma_{Y,\,\mathrm{Base}} = f(d) \times \{\mathrm{KBCON} + \mathrm{KBCU} \times \mathrm{Cu}(z_r) + \mathrm{KBSX} \times \sigma'_x + \mathrm{KBSY} \times \sigma'_y + \mathrm{KBSZ} \times \sigma'_z\}$$
$$\tau_{Y,\,\mathrm{Ax}} = f(d) \times \{\mathrm{KVCON} + \mathrm{KVCU} \times \mathrm{Cu}(z_r) + \mathrm{KVSX} \times \sigma'_x + +\mathrm{KVSY} \times \sigma'_y + \mathrm{KVSZ} \times \sigma'_z\}$$
$$\sigma_{Y,\mathrm{Perp}} = f(d) \times \{\mathrm{KHCON} + \mathrm{KHCU} \times \mathrm{Cu}(z_r) + \mathrm{KHSX} \times \sigma'_x + \mathrm{KHSY} \times \sigma'_y + \mathrm{KHSZ} \times \sigma'_z\}$$

Here d is relative displacement (see Remark 12), z_r is the relative Z-coordinate as defined above, and σ'_x, σ'_y and σ'_z are the soil stresses in the global X, Y and Z directions, respectively. If pore water is modeled (see *CONTROL_PORE_-FLUID), then these are "effective stresses", meaning the stress generated by the material model excluding any pore pressure. Note that *CONSTRAINED_-SOIL_PILE does not require pore pressure to be modelled.

The depth-dependence function, $\mathrm{Cu}(z_r)$, is defined as follows: If LCCU is zero or blank, $\mathrm{Cu}(z_r) = \mathrm{ACU} + \mathrm{BCU} \times z_r$. Otherwise, $\mathrm{Cu}(z_r) = \mathrm{LCCU}(z_r)$.

The function $f(d)$ has three possible forms, illustrated here for Base coupling (input parameters BLC and BHYPER), but the same rules apply for Axial coupling (VLC and VHYPER) and Perpendicular coupling (HLC and HHYPER).

a) If BHYPER and BLC are both zero, $f(d)$ is unity, resulting in a bilinear elastic-perfectly-plastic coupling characteristic.

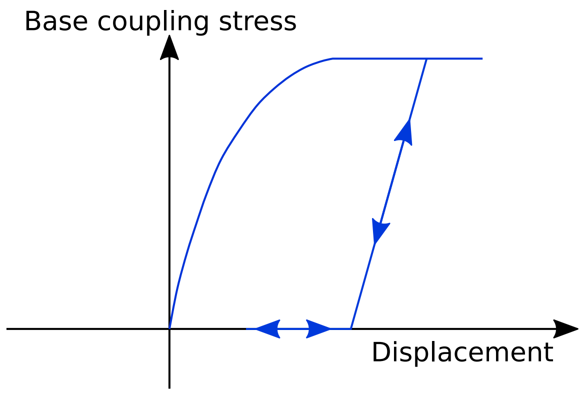

Figure 0-2. Base coupling unload/reload behavior

b) If the load curve BLC is nonzero, $f(d)$ is the value of the load curve. BLC is an optional load curve (see *DEFINE_CURVE) giving a non-dimensional factor on yield stress as a function of displacement.

c) If BHYPER is nonzero (typical value: 0.95), the stress as a function of displacement follows a hyperbolic curve:

$$f(d) = \min\left[1.0, \quad d_{\max} \big/ \mathrm{BHYPER} \times (d_{\mathrm{elastic}} + d_{\max})\right] .$$

Here $d_{\max}$ is the maximum displacement that has occurred so far, and d_{elastic} is the elastic displacement calculated (for the example of Base coupling) from $\sigma_{\max}/S_{\mathrm{Base}}$. $\sigma_{\max}$ is the stress term in curly brackets in the equation for $\sigma_{Y,Base}$ above.

The three options for $f(d)$ are illustrated in Figure 0-1.

7. **Backbone Coupling Curves when *OPTION1* is CURVES.** The coupling stresses for Base, Axial and Perpendicular coupling (σ_{Base}, τ_{Ax}, and σ_{Perp}, respectively) are defined as follows:

$$\sigma_{\mathrm{Base}} = \left\{\mathrm{BLCZ}(z_r) + 0.5\left(\sigma'_x + \sigma'_y\right) \times \mathrm{BLCSH}(z_r) + \sigma'_z \times \mathrm{BLCSV}(z_r)\right\} \times \mathrm{BLC}(d)$$
$$\tau_{\mathrm{Ax}} = \left\{\mathrm{VLCZ}(z_r) + 0.5\left(\sigma'_x + \sigma'_y\right) \times \mathrm{VLCSH}(z_r) + \sigma'_z \times \mathrm{VLCSV}(z_r)\right\} \times \mathrm{VLC}(d)$$
$$\sigma_{\mathrm{Perp}} = \left\{\mathrm{HLCZ}(z_r) + 0.5\left(\sigma'_x + \sigma'_y\right) \times \mathrm{HLCSH}(z_r) + \sigma'_z \times \mathrm{HLCSV}(z_r)\right\} \times \mathrm{HLC}(d)$$

Here d is relative displacement (see Remark 12). z_r is the relative Z-coordinate defined as $Z_0 - \mathrm{ZREF}$. Z_0 is the initial Z-coordinate of the pile node). σ'_x, σ'_y and σ'_z are the stresses in the global X, Y and Z directions. If pore water is modeled (see *CONTROL_PORE_FLUID), then these are “effective stress” meaning the stress generated by the material model excluding any pore pressure. Note that *CONSTRAINED_SOIL_PILE does not require pore pressure to be modelled.

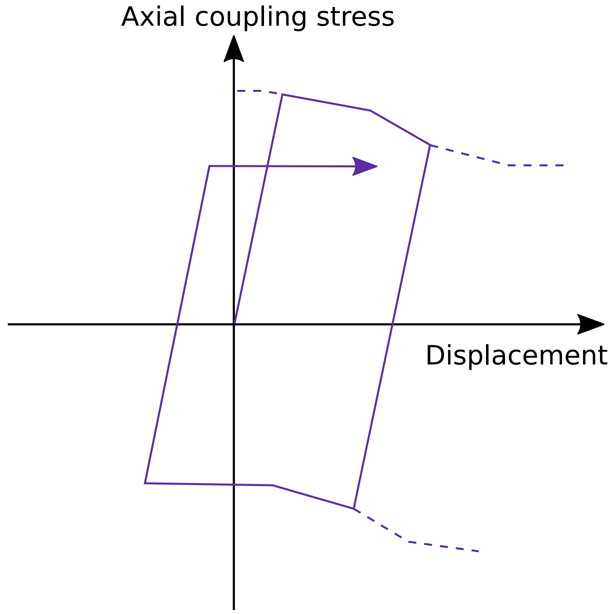

Figure 0-3. Axial coupling unload/reload behavior

The "normalized mobilization curves" BLC, VLC, HLC, if defined, must have a first point at (0,0). The initial elastic coupling stiffness is determined from the above equations using the gradient of the line between the first and second points of the normalized mobilization curve. If any of the curves (BLCZ, BLC, VLCZ, HLCSH, etc.) are left blank, the corresponding term in the above equations is set to zero. For example, if BLC is left blank than the Base coupling stress will always be zero, meaning no Base coupling.

8. **Directionality of loading and unload/reload behavior: Base coupling.** Base coupling resists relative movement only in the axial direction corresponding to a pile being pressed downwards into the soil. This coupling results in a compressive axial load on the pile. Uplift is not resisted and results in a gap between the base of the pile and the soil. On reloading, any gap must close before compressive loading of the pile can resume. Figure 0-2 illustrates this unloading/reloading behavior for when BHYPER on Card 4a specifies the shape of the coupling.

9. **Directionality of loading and unload/reload behavior: Axial coupling.** Axial coupling shear stresses resist sliding of the pile in both axial directions. An elasto-plastic approach is adopted. Thus, if the direction of axial movement is reversed, stresses also reverse. Figure 0-3 illustrates a possible response when a user-defined mobilization curve VLC is specified.

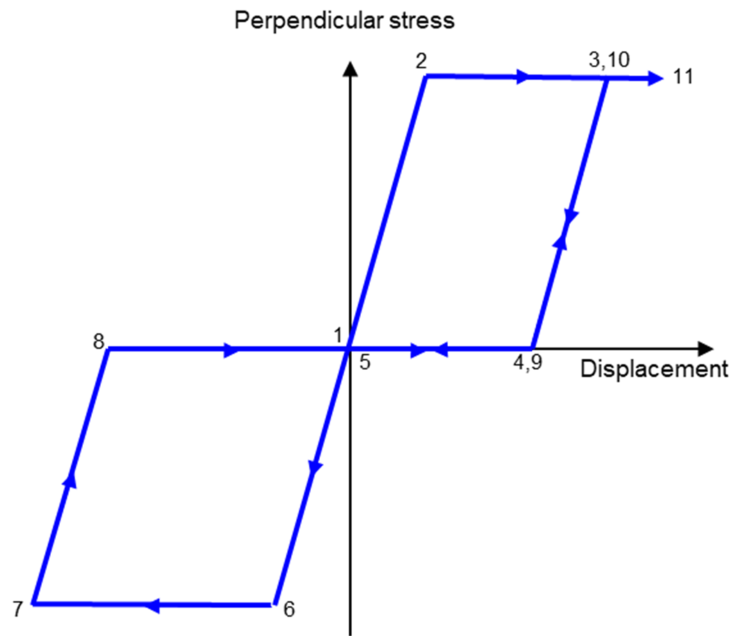

Figure 0-4. Perpendicular coupling unload/reload behavior

10. **Directionality of loading and unload/reload behavior: Perpendicular coupling.** Perpendicular coupling stresses are calculated such that, if a cyclical back-and-forth motion is applied to a pile, the effect is that of an elongating hole (sometimes called "post-hole" behavior named for the observed behavior of the hole in the ground when a fence-post is repeatedly bent in one direction and then the other). As an illustration, in Figure 0-4, HLC and HHYPER are left blank, and a cycling motion is applied.

    Movement could potentially occur at any angle in the plane perpendicular to the pile axis. The input coupling characteristics are applied, and any gaps tracked, for 8 directions at 45-degree intervals around the pile circumference. For or intermediate angles of movement, an interpolation method is used resulting in small differences between the input stress-displacement coupling characteristic and the one achieved by the model.

11. **Location of coupling points.** LS-DYNA calculates the coupling stresses at each coupling point using the input coupling characteristics. By default (NRING = 0 or 1), one coupling point is coincident with each pile node. We recommend the default when the solid element size is greater than or equal to the pile diameter. Where the soil elements are smaller than the pile diameter, we recommend distributing the coupling stresses onto all the soil elements through which the outer surface of the pile passes. To do this, specify a value of NRING > 1 to define a ring of coupling points level with each pile node around the circumference of the pile. Typically, you should select a value of NRING such that about 1 or 2 coupling points are present in each soil element

on the circumference of the pile. Irrespective of the setting of NRING, we recommend NRINGB = 0, meaning that the coupling points on the base of the pile are automatically chosen to obtain an approximately uniform distribution. NRING and NRINGB influence the coupling point mesh only in the plane perpendicular to the pile axis. There is no option to refine the coupling point mesh in the axial direction. See Figure 0-5 for illustration.

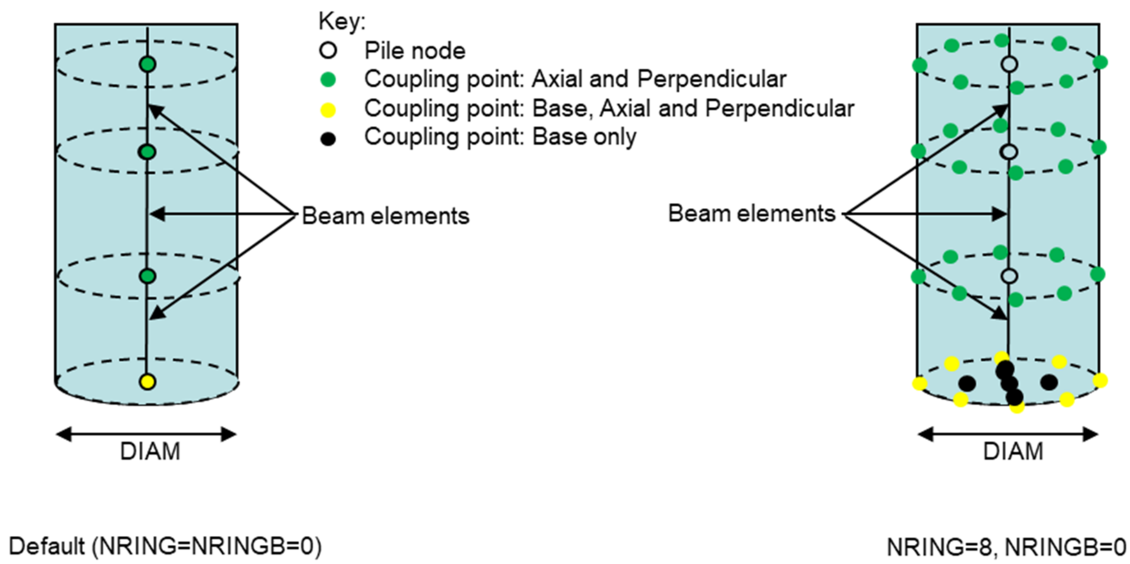

Figure 0-5. Location of coupling points

12. **Definition of displacement of the pile relative to the soil.** Relative displacement at a given coupling point is the difference of displacement between a pile point and a soil point. The pile point displacement is calculated as if a rigid link were present between the pile node and the coupling point. Therefore, when NRING > 1, the rotation of the pile node times the radial offset between pile node and coupling point contributes to the displacement. The soil point retains a constant relative position (iso-parametric coordinates) within the soil element. These calculations do not create any additional constraints on the pile node or soil nodes.

13. **Relation between coupling stress and force on the pile.** The Base, Axial and Perpendicular coupling forces are calculated at each coupling point from the coupling stresses as follows:

$$
\begin{aligned}
F_{\mathrm{Base}} &= \sigma_{\mathrm{Base}} A_{\mathrm{Bp}} \\
F_{\mathrm{Ax}} &= \tau_{\mathrm{Ax}} \times \pi D \times 0.5(L_1 + L_2)/\mathrm{NRING} \\
F_{\mathrm{Perp}} &= \sigma_{\mathrm{Perp}} \times D \times 0.5(L_1 + L_2)/\mathrm{NRING}
\end{aligned}
$$

Here A_{Bp} is the area associated with a Base coupling point, D is the pile diameter (DIAM), and L_1 and L_2 are the lengths of the two pile beam elements that meet at the pile node in question. Note that the axial force is based on the whole perimeter being loaded by the shear stress, while the perpendicular force is based on the stress times the area of the pile projected in the perpendicular direction.

The coupling forces are applied to the pile node and reacted on the nodes of the soil element containing the coupling point. If NRING > 1, moments arising from the coupling force times the radial offset between the pile node and the coupling point are applied to the pile node.

14. **Coupling visualization elements.** LS-DYNA automatically creates a beam element at each coupling point. These are for visualizing the coupling stresses only; they do not create additional forces in the solution. You must define the *PART, *SECTION and *MAT cards for two parts with part IDs PIDNS and PIDNB into which these beam elements will be placed. PIDNB is for visualizing Base coupling, while PIDNS is for visualizing Axial and Perpendicular coupling. You should not define any elements with these part IDs (the elements will be generated automatically). Note the following points:

    a) On *SECTION, ELFORM must be 6.

    b) The mass and inertia should have small nonzero values,

    c) The material type must be 9 (*MAT_NULL).

15. **Viewing the coupling stresses.** In the d3plot output file, the coupling visualization beam elements contain fake forces which are actually the coupling stresses. For the elements in part PIDNS, Axial force (or X-Force) is really the Perpendicular coupling stress in the local x direction; Y-Shear (or Y-Force) is really the Perpendicular coupling stress in the local y direction; and, Z-Shear (or Z-Force) is really the Axial coupling stress.

    For the elements in part PIDNB, the Axial force (or X-Force) and Y-Shear (or Y-Force) are zero, and the Z-Shear (or Z-Force) is really the Base coupling stress.

    The nodes of the visualization beam elements stay coincident with the pile and soil coupling points mentioned in Remark 11 throughout the analysis, enabling visualization of the pile/soil relative displacements (see Remark 12).

16. **Depth-dependent properties.** Soil stiffness and strength generally increases with depth. Soil-pile coupling properties are related to soil properties and therefore they also tend to increase with depth. *CONSTRAINED_SOIL_PILE offers options for defining coupling properties that vary with depth (expressed via functions of Z-coordinate relative to ZREF), but depth-dependent coupling could also be achieved by defining multiple layers of soil each with a different part ID, and then defining unique but non-depth-dependent properties for each layer.

17. **Damping.** Damping of the axial response may be defined using DAMP. This is not usually required for quasi-static simulations for which other damping methods are available, so DAMP is usually set to zero. However, damping may sometimes be desirable in some dynamic simulations.

18. **Mass-scaling.** LS-DYNA checks the numerical stability of the coupling, based on the coupling stiffness and the masses of the pile and soil nodes. If the model uses mass-scaling (negative DT2MS on *CONTROL_TIMESTEP), and if a coupling point would not otherwise be stable at the current timestep, LS-DYNA will automatically add mass to the pile and soil nodes to ensure stability. The mass added by *CONSTRAINED_SOIL_PILE during the first timestep is printed to the d3hsp file; search for "added mass for *CONSTRAINED_SOIL_PILE". If the amount of added mass seems excessive, consider reducing the initial elastic coupling stiffness (described in Remarks 6 and 7).

19. **Calibration of coupling properties.** The nonlinear coupling properties in *CONSTRAINED_SOIL_PILE account for the part of the deformation of the soil that is not captured explicitly by the soil mesh. The finer the soil mesh, the more localized deformation around the pile will be captured by the soil elements, and therefore the less deformation needs to be accounted for by the coupling properties. Thus, realistic input properties for *CONSTRAINED_SOIL_PILE depend on soil mesh size. It is advisable to calibrate the input properties against a detailed model in which the pile (or part of a pile) is represented by solid elements embedded in finely-meshed soil and subjected to axial and perpendicular loading cases.