* **Modification of stress path method for settlement computation of normally consolidated clays (Kim et al. (2011))**

1) Gradual change of Poisson's ratio during consolidation
   Ex) Circular footing under uniform vertical loading ($\nu_u = 0.5 \rightarrow \nu_d = 0.1$)

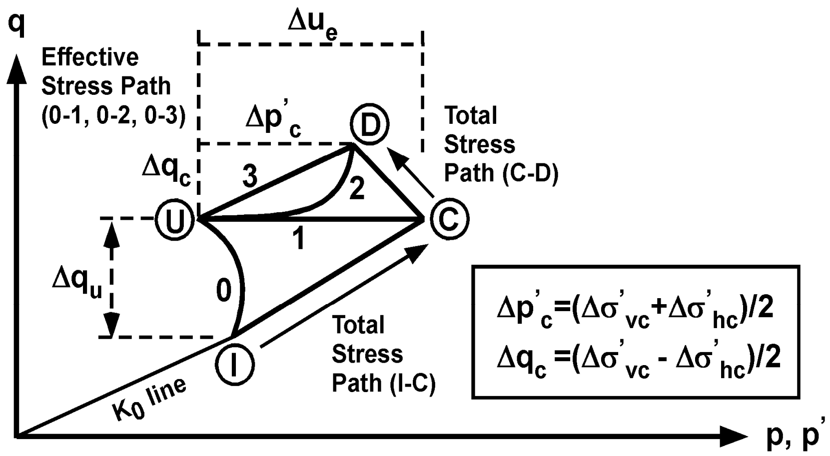


Fig. 2-26 Typical Stress Path of Soil Element

Based on the equation proposed by Poulos and Davis as below,

$$\Delta\sigma_v = p_0\left[1-\left\{\frac{1}{1+(a/z)^2}\right\}^{3/2}\right] \text{ and}$$

$$\Delta\sigma_h = \frac{p_0}{2}\left[(1+2\nu)-\frac{2(1+\nu)}{(1+(a/z)^2)^{1/2}}+\frac{1}{(1+(a/z)^2)^{3/2}}\right] \qquad \text{(Eq. 2-1)}$$

Where, a is the radius of the circular footing
p_0 is the pressure acting on the circular area
z is the depth from the surface
ν is the poisson's ration of the elastic half space

the paths C-D in Fig. 2-27 indicate the changes of total stresses. (significant in shallow depth)

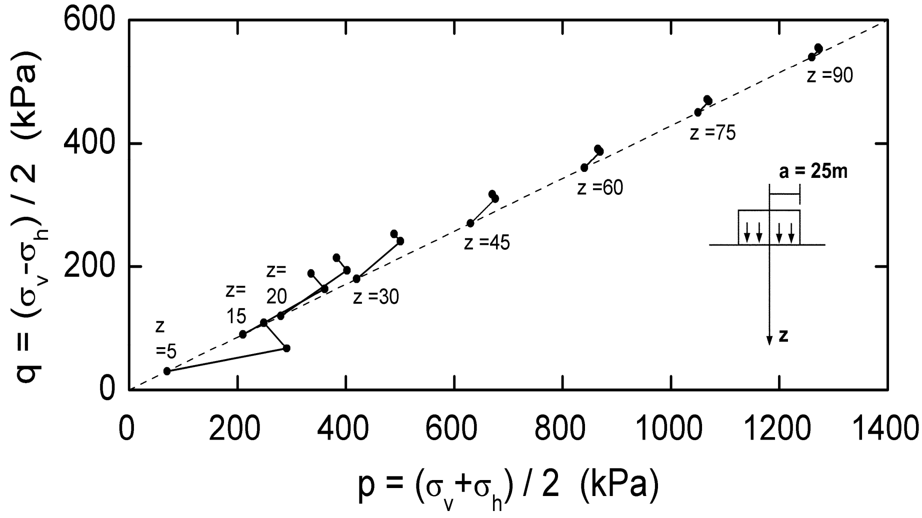


Fig. 2-27 Variation of Total Stress Paths for Various Depths of the Circular Footing

Figure 2-28 shows the ratio of the length of the stress path C-D to the length of the path I-C. (i.e. the relative magnitude of the total stress change during consolidation)

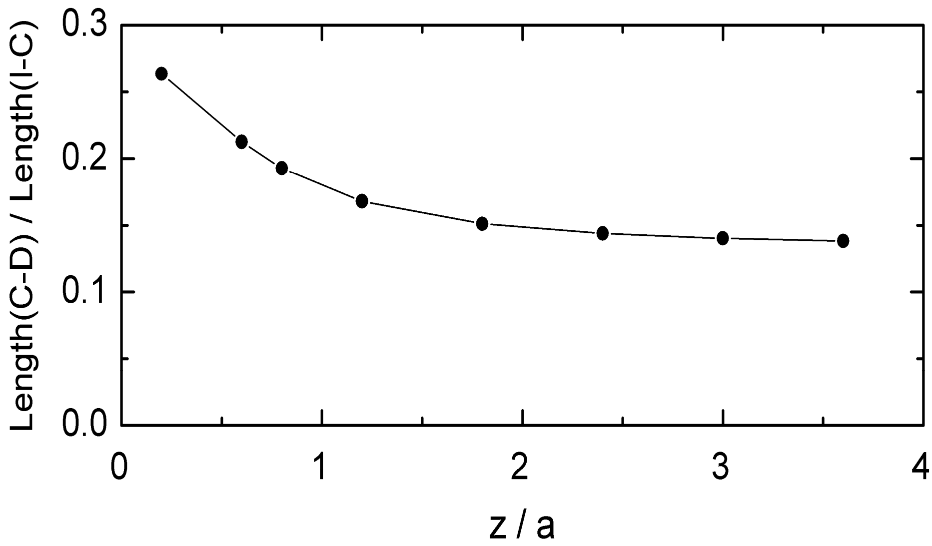


Fig. 2-28 Relative Length of Total Stress Path

2) New Testing concept for stress path method.

- Normalized stress-strain behavior by the initial stress state.
  → The normally consolidated clay exhibits the similar stress strain behavior when the stresses are normalized by the initial stress on the K_0 state. (Atkinson and Branshy (1978))

- Immediate settlements determined by deviator stress and not by mean normal stress.
  → Unique relationship between S_i and $\Delta\sigma_d$.

- Back pressure equalization.
  - Conventional dissipation process, initiated by opening a drainage valve. → provides isotropic stress path(U-C).
  - After undrained loading, we increase the back pressure as the same amount as the excess pore pressure and then open the drainage valve.

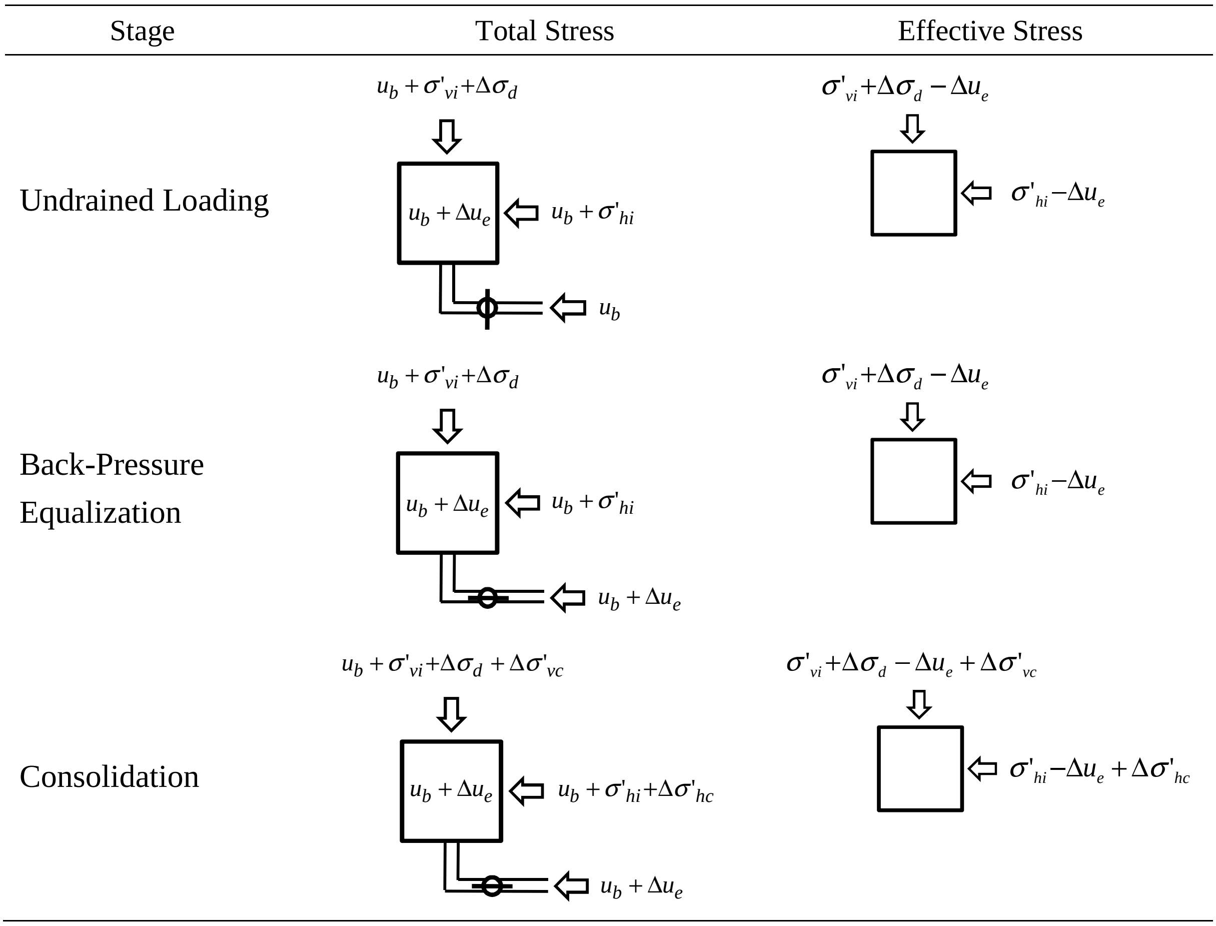


Fig. 2-29 Stresses of Soil Element During Back Pressure Equalization

- The back pressure equalization makes it possible to perform the test of the any stress paths including anisotropic stress path.
- Additionally, it provides a methodology to measure effective stress-strain relationship at every stress points along the given consolidation stress path.

• Charactering stress-strain behavior of clays.

- The constitutive relationship in the triaxial condition;

$$\begin{bmatrix} \varepsilon_{vc} \\ \varepsilon_{hc} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \Delta\sigma'_{vc} \\ \Delta\sigma'_{hc} \end{bmatrix} \qquad \text{(Eq. 2-2)}$$

- To determine A, B, C, D, two sets of the stress-strain data with different K_c $(=\Delta\sigma'_{hc}/\Delta\sigma'_{vc})$ are required.

$$\begin{bmatrix}(\varepsilon_{vc})_I & (\varepsilon_{vc})_{II} \\ (\varepsilon_{hc})_I & (\varepsilon_{hc})_{II}\end{bmatrix} = \begin{bmatrix}A & B \\ C & D\end{bmatrix}\begin{bmatrix}(\Delta\sigma'_{vc})_I & (\Delta\sigma'_{vc})_{II} \\ (\Delta\sigma'_{hc})_I & (\Delta\sigma'_{hc})_{II}\end{bmatrix}$$

$$= \begin{bmatrix}A & B \\ C & D\end{bmatrix}\begin{bmatrix}\frac{2}{1+(K_c)_I}(\Delta p'_c)_I & \frac{2}{1+(K_c)_{II}}(\Delta p'_c)_{II} \\ \frac{2(K_c)_I}{1+(K_c)_I}(\Delta p'_c)_I & \frac{2(K_c)_{II}}{1+(K_c)_{II}}(\Delta p'_c)_{II}\end{bmatrix}$$

(Eq. 2-3)

- The compliance parameters, A, B, C, and D are not constant due to nonlinear stress-strain behavior of clays.

→ Iteration procedure with the constant strain energy concept is adopted. ($W = \frac{1}{2}(\Delta\sigma'_{vc}\,\varepsilon_{vc} + 2\Delta\sigma'_{hc}\,\varepsilon_{hc}$)

$$= \left[A + (B+2C)K_c + 2DK_c^2\right]\frac{2(\Delta p'_c)^2}{(1+K_c)^2})$$ (Eq. 2-4)

→ The strains can be computed using the converged set of the parameters, A, B, C, and D.

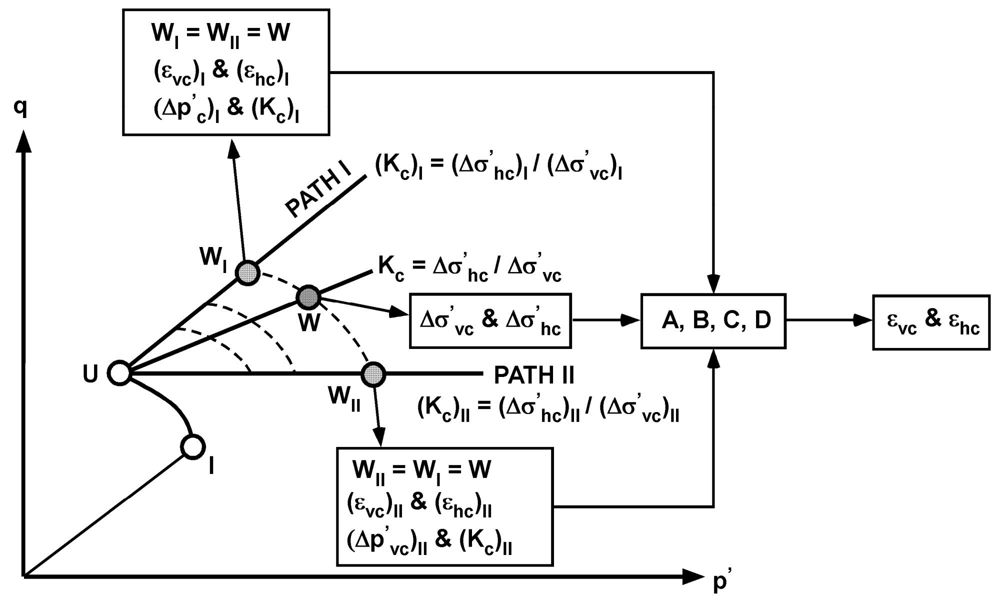


Fig. 2-30 Evaluating Strains For Consolidation Loading

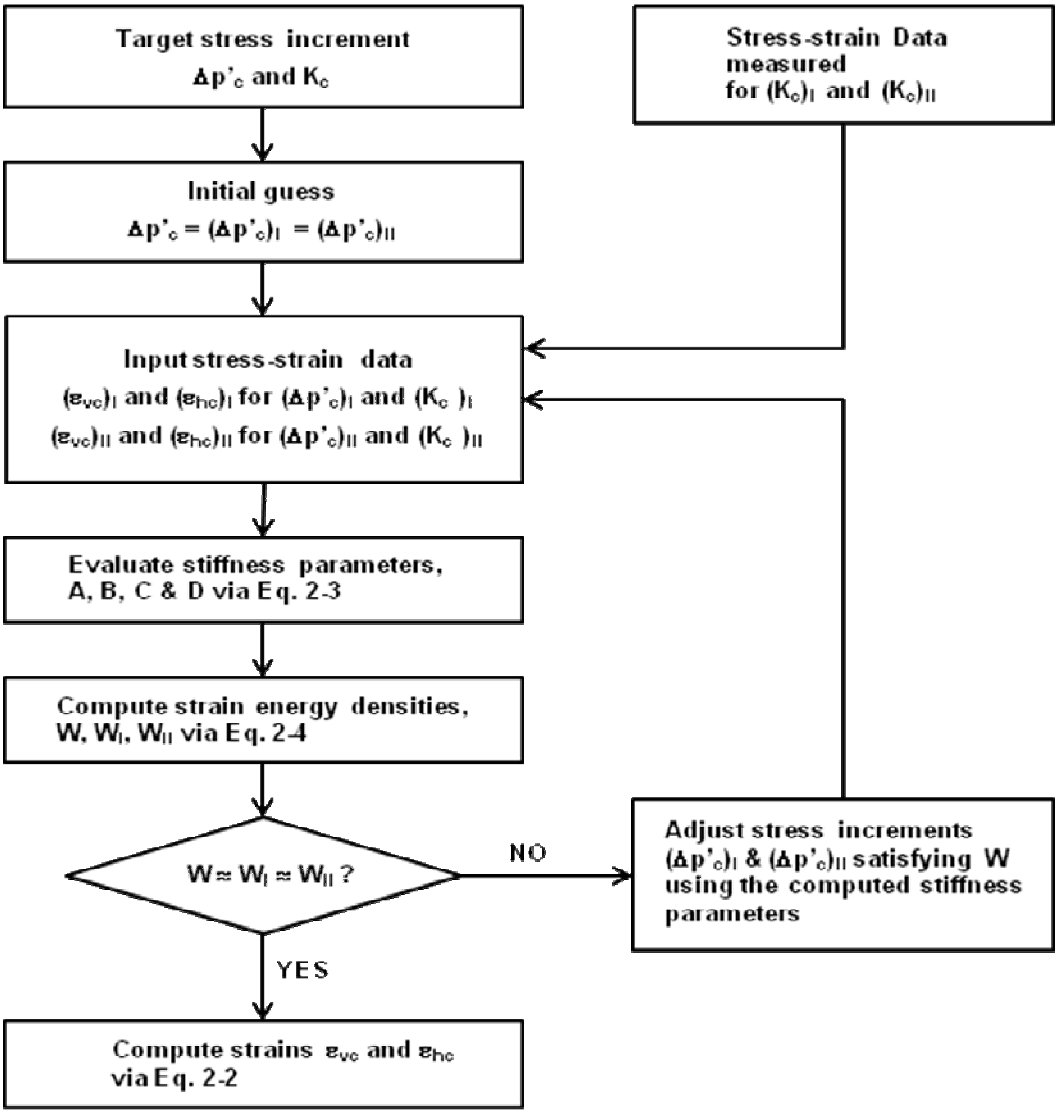


Fig. 2-31 Flow of the Proposed Stress Path Method

3) Experimental application.
- Soils → Reconstituted kaolinite specimens. (PI=23.3, CL)
- Stress path tests
  - Back pressure saturation
  - Reconsolidated under K_0 condition $\sigma'_{vc(\max)} = 200\,kPa$ (twice larger than maximum past pressure)
  - Undrained loading followed back pressure equalization.
    → The axial stress was incrementally increased by 3.0 kPa.

- Then, consolidated with a selected stress path of K_c values.
  → Axial and horizontal stresses were applied at a rate of 0.8 kPa/h.
- Test summary

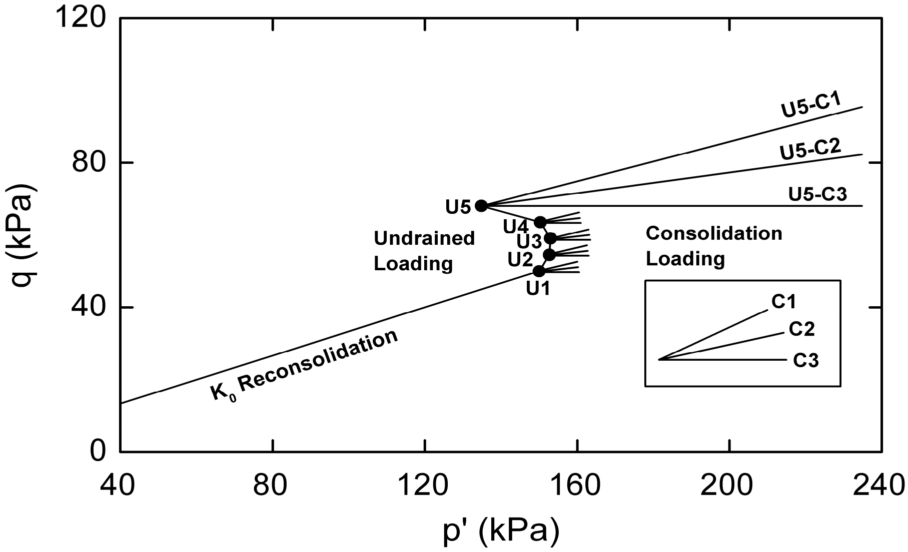


Fig. 2-32 Consolidation and Stress Probing Paths

→ 5 undrained loadings under 3 stress path tests with K_c = 0.57, 0.75, 1.00 were performed.

- Test results
  ① Undrained loading results

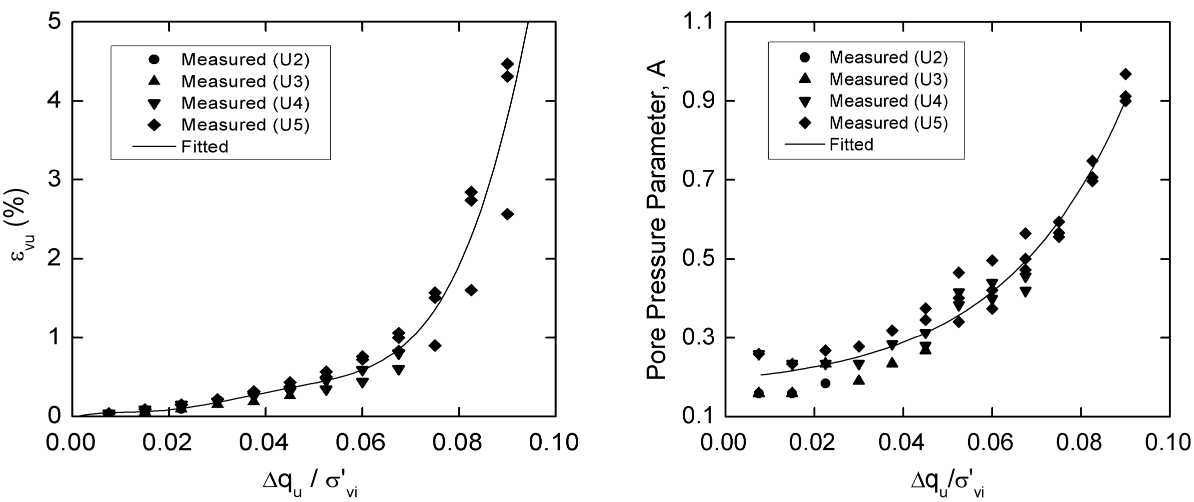


Fig. 2-33 Vertical Strain and Pore Pressure Parameter During Undrained Loading

② Stress path loading results

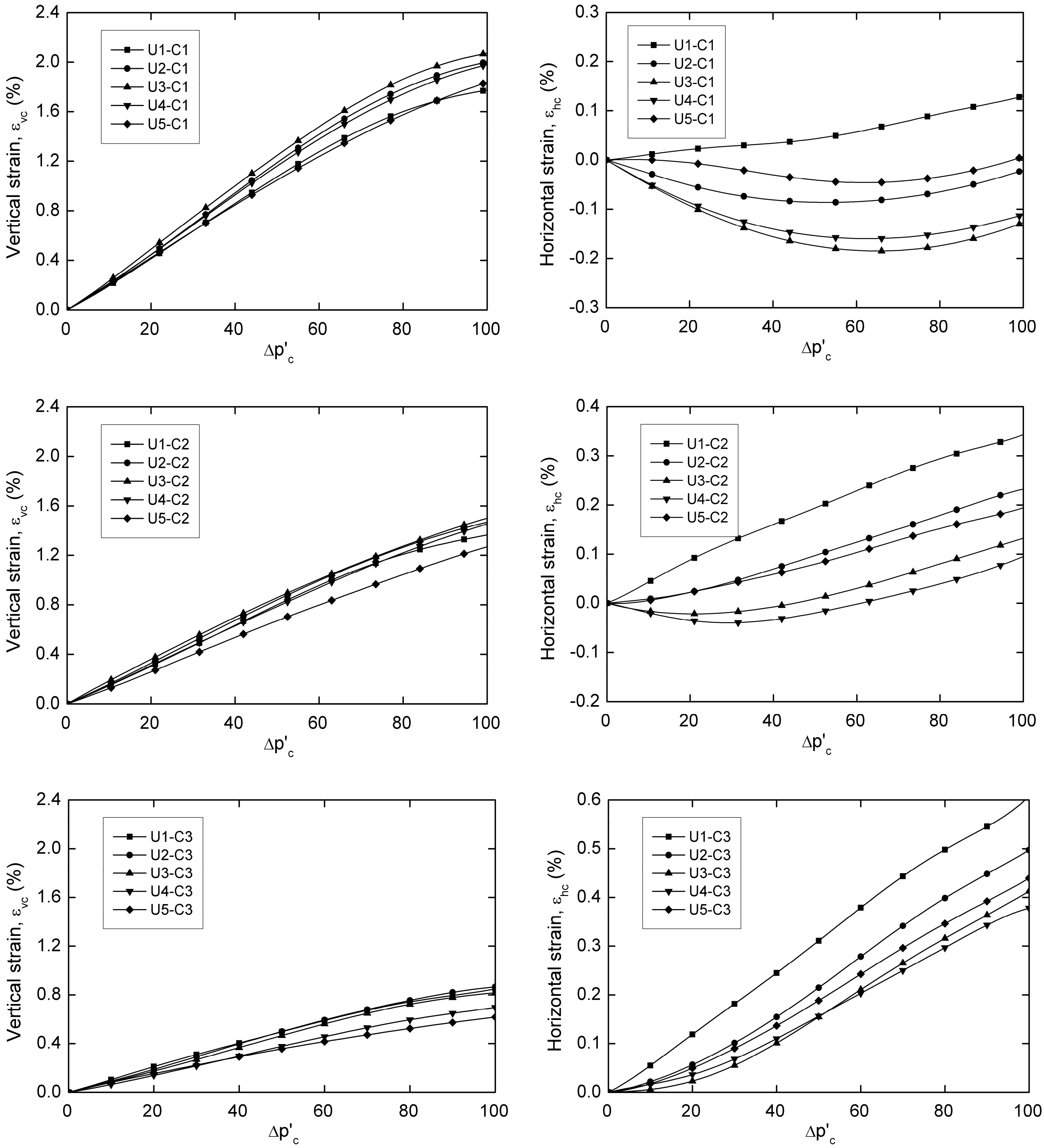


Fig. 2-34 Stress-Strain Responses During Consolidation

③ Strain energy contour

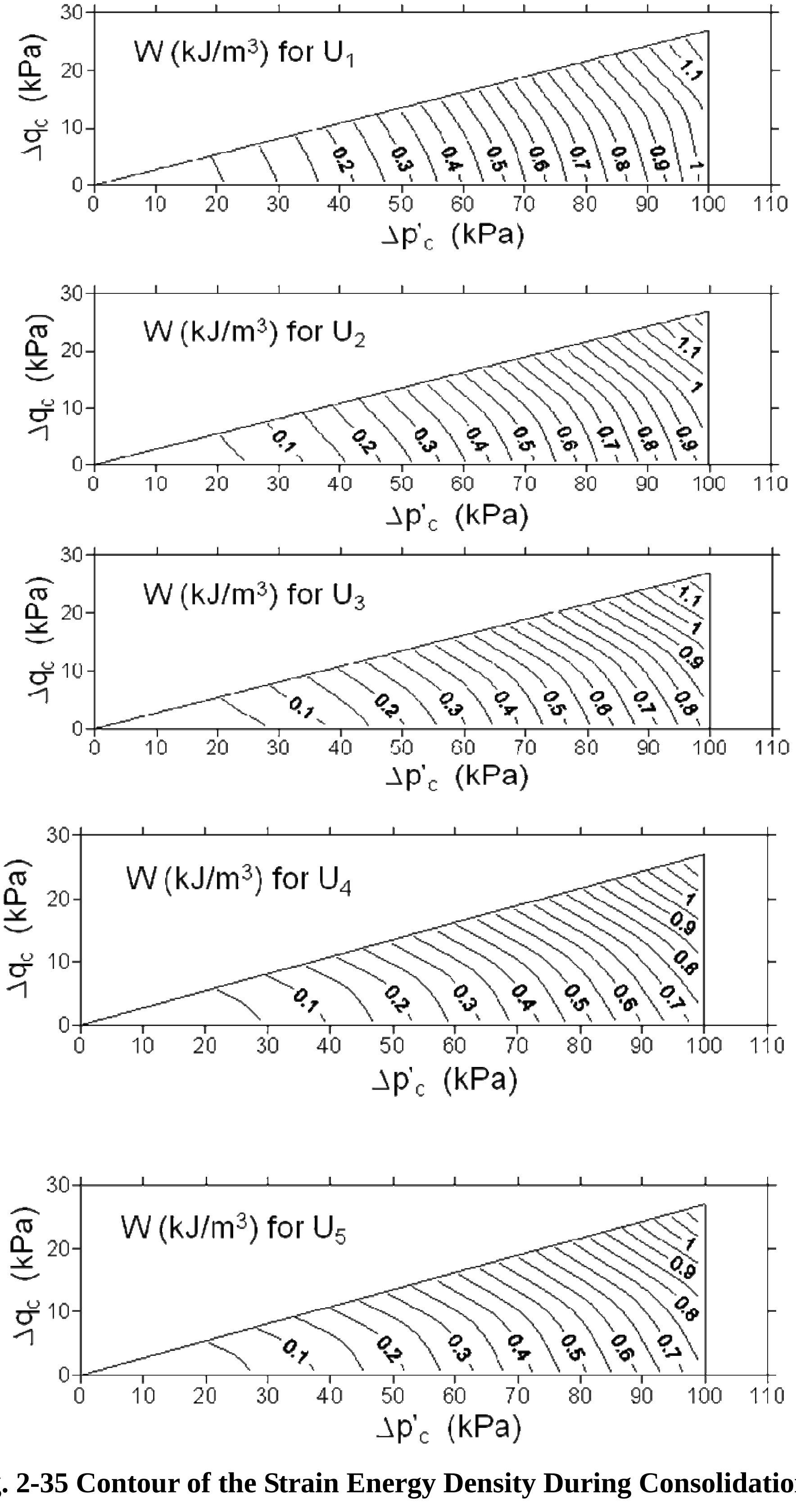
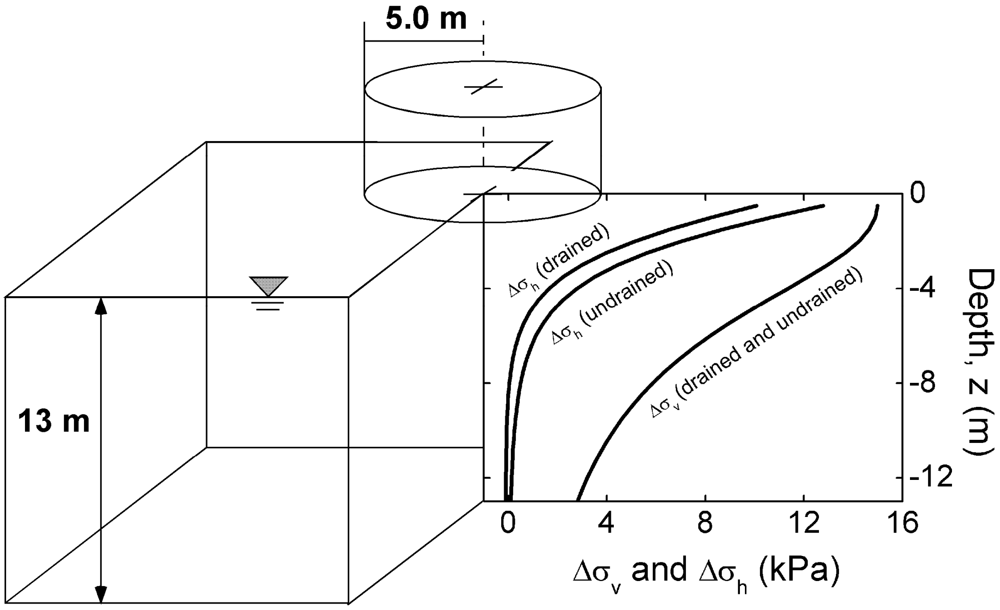


Fig. 2-35 Contour of the Strain Energy Density During Consolidation

4) An example of evaluating consolidation settlement

- Given conditions



- Circular footing with r=5m, and applied pressure, $p_0 = 15\,kPa$
- 13m deep clay stratum(fully saturated)

Table 2-4 Summary of index properties and consolidation characteristics

Unit weight (kN/m^3)	17.0
Specific Gravity	2.59
Liquid Limit (%)	44.4
Plasticity Index (%)	23.3
Percentage passing through #200 sieve (%)	98.0
Unified Classification	CL
Natural Water Content (%)	37.6 ~ 40.2
Max. Past Pressure (kPa)	98 ~ 116
Compression Index	0.253 ~ 0.286
Recompression Index	0.110 ~ 0.126
Permeability (10^{-9} m/s)	5.24 ~ 29.3

- Initial stresses at the depth of 6.5m

  $\sigma'_{vi} = 46.7kPa,\ \sigma'_{hi} = 23.4kPa$

- Elastic solutions at the depth of 6.5m

  → With $\nu = 0.5$, $(\Delta\sigma_v)_u$ = 7.55 kPa and $(\Delta\sigma_h)_u$ = 0.90 kPa

  → With $\nu = 0.3$,$(\Delta\sigma_v)_d$ = 7.55 kPa and $(\Delta\sigma_h)_d$ = 0.30 kPa.

• The settlement computation

- $\Delta q_u / \sigma'_{vi} = ((\Delta\sigma_v)_u - (\Delta\sigma_h)_u)/2\sigma'_{vi}$ =0.071

  → Fig. 2-33 gives ε_{vu} =1.12%, A = 0.54.

  → $\Delta u_e = A((\Delta\sigma_v)_u - (\Delta\sigma_h)_u) + (\Delta\sigma_h)_u$ =4.49 kPa

- The change of the effective stresses during consolidation

  $\Delta\sigma'_{vc} = (\Delta\sigma_v)_d - (\Delta\sigma_v)_u + \Delta u_e$ =7.55 – 7.55 + 4.49=4.49 kPa

  $\Delta\sigma'_{hc} = (\Delta\sigma_h)_d - (\Delta\sigma_h)_u + \Delta u_e$ =0.30 – 0.90 + 4.49=3.89 kPa

  ⇒ $\Delta p'_c = (\Delta\sigma'_{vc} + \Delta\sigma'_{hc})/2 = 4.19$ kPa

  $K_c = \Delta\sigma'_{hc} / \Delta\sigma'_{vc} = 0.87$

- For K_c =0.87 and $\Delta p'_c / \sigma'_{vi} = 4.19/46.7$ =0.090, ε_{vc}, in the middle of the stratum is estimated 0.22%, based on iteration procedure,

Table 2-5 Iteration procedure in computing consolidation strain

Iteration	Input stress increment		Normalized stress increment		Computed strain (%)			
1st	$(\Delta p'_c)_I$	$(\Delta p'_c)_{II}$	$\frac{(\Delta p'_c)_I}{\sigma'_{vi}}$	$\frac{(\Delta p'_c)_{II}}{\sigma'_{vi}}$	$(\varepsilon_{vc})_I$	$(\varepsilon_{hc})_I$	$(\varepsilon_{vc})_{II}$	$(\varepsilon_{hc})_{II}$
	4.188	4.188	0.090	0.090	0.406	-0.067	0.123	0.034
	Stiffness parameters (MPa^{-1})				Strain energy density (kJ/m^3)			
	A	B	C	D	W	W_I		W_{II}
	1.381	-1.234	-0.397	0.438	0.283	0.725		0.200
2nd	$(\Delta p'_c)_I$	$(\Delta p'_c)_{II}$	$\frac{(\Delta p'_c)_I}{\sigma'_{vi}}$	$\frac{(\Delta p'_c)_{II}}{\sigma'_{vi}}$	$(\varepsilon_{vc})_I$	$(\varepsilon_{hc})_I$	$(\varepsilon_{vc})_{II}$	$(\varepsilon_{hc})_{II}$
	2.617	4.982	0.056	0.107	0.254	-0.043	0.149	0.043
	Stiffness parameters (MPa^{-1})				Strain energy density (kJ/m^3)			
	A	B	C	D	W	W_I		W_{II}
	1.378	-0.736	-0.416	0.603	0.931	0.487		1.260
10th	$(\Delta p'_c)_I$	$(\Delta p'_c)_{II}$	$\frac{(\Delta p'_c)_I}{\sigma'_{vi}}$	$\frac{(\Delta p'_c)_{II}}{\sigma'_{vi}}$	$(\varepsilon_{vc})_I$	$(\varepsilon_{hc})_I$	$(\varepsilon_{vc})_{II}$	$(\varepsilon_{hc})_{II}$
	3.190	4.469	0.068	0.096	0.310	-0.052	0.132	0.037
	Stiffness parameters (MPa^{-1})				Strain energy density (kJ/m^3)			
	A	B	C	D	W	W_I		W_{II}
	1.380	-1.015	-0.408	0.510	0.563	0.568		0.552
20th	$(\Delta p'_c)_I$	$(\Delta p'_c)_{II}$	$\frac{(\Delta p'_c)_I}{\sigma'_{vi}}$	$\frac{(\Delta p'_c)_{II}}{\sigma'_{vi}}$	$(\varepsilon_{vc})_I$	$(\varepsilon_{hc})_I$	$(\varepsilon_{vc})_{II}$	$(\varepsilon_{hc})_{II}$
	3.211	4.458	0.069	0.095	0.312	-0.052	0.132	0.037
	Stiffness parameters (MPa^{-1})				Strain energy density (kJ/m^3)			
	A	B	C	D	W	W_I		W_{II}
	1.380	-1.022	-0.408	0.508	0.555	0.554		0.555
Final	$\varepsilon_{vc} = A\Delta\sigma_{vc} + B\Delta\sigma_{hc} = 1.380\text{MPa}^{-1} \times 4.49\text{kPa} - 1.022\text{MPa}^{-1} \times 3.89\text{kPa} = 0.22\%$							

strains	$\varepsilon_{hc} = C\Delta\sigma'_v + D\Delta\sigma'_h = -0.408\text{MPa}^{-1} \times 4.49\text{kPa} + 0.508\text{MPa}^{-1} \times 3.89\text{kPa} = 0.01\%$

- The settlement,

$$\rho = \int_0^H \varepsilon_v dz \approx (\varepsilon_{vu} + \varepsilon_{vc})H \quad = (1.12\% + 0.22\%) \times 13 \text{ m} = 17 \text{ cm}$$

- For further precise computation, the clay stratum could be divided into several layers.