ITA/AITES – Training Course
TUNNEL ENGINEERING

Cut and cover tunnels in metropolitan areas

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Introduction

The cut and cover construction technique has been used for many years as a means for building underground transportation facilities.

This method involves the installation of temporary walls to support the sides of the excavation, a bracing system, control of ground water, and underpinning of adjacent structures where necessary.

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Economy dictates that transportation and utilities are placed as near as the surface as possible and constructed by cut and cover techniques rather than by tunneling methods. Shallow cut and cover tunnels have several other advantages such as easy access from street level.

The main disadvantages of a cut and cover tunnel are its disruptive effects in congested urban environment.

Cost of cut and cover construction increases sharply with increased depth. Tunnel driving costs are usually higher per meter of tunnel than the average shallow cut and cover tunnel.

Ground Support Systems

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Cut and cover construction contracts generally permit a contractor to design the ground support system.

Minimum design criteria include the method of calculation of lateral earth pressures for dewatered and non-dewatered conditions, traffic and equipment loads, building surcharge loads, design standards to be used in the design of the excavation support system.

Intermediate phases of the construction are generally more critical than the end of construction stage, and govern the design of structural members.

Ground Support Systems

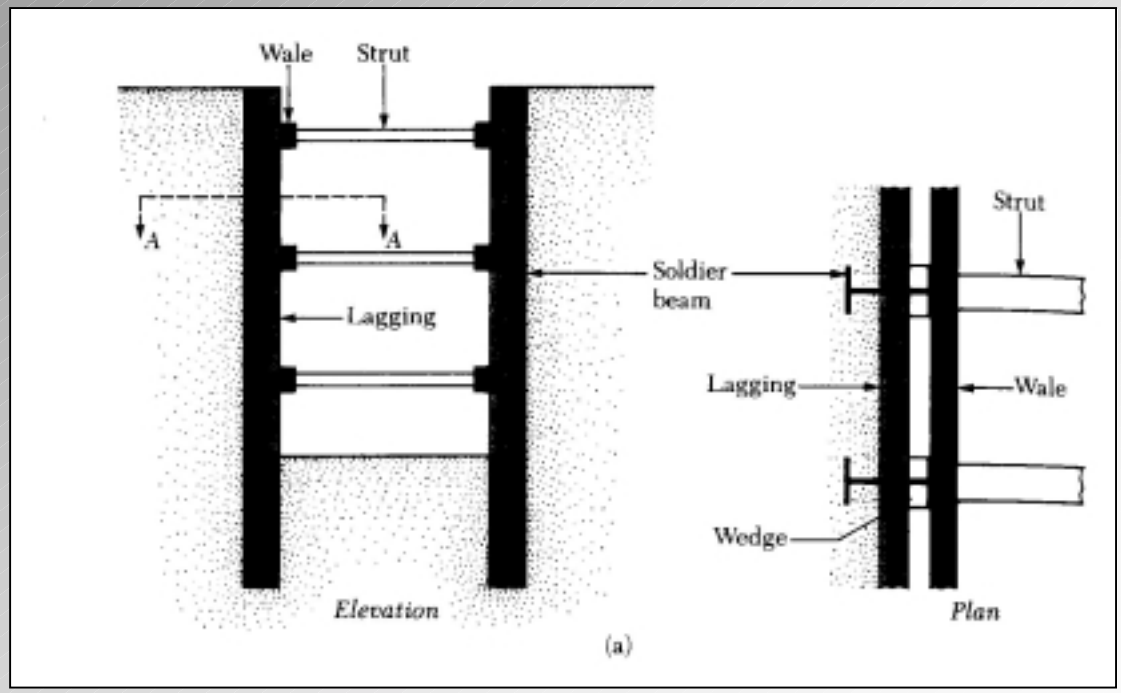
Several types of support systems are used, employing various techniques and materials, but these systems can be divided into flexible and semi-rigid wall systems, in general (Wickham and Tiedemann, 1976). The degree of elasticity and yielding is the major difference between the two systems.

Examples of the semi-rigid walls include diaphragm walls such as the reinforced concrete slurry walls and interlocking concrete piles. An example for the flexible walls is steel sheet piles.

Ground Support Systems

Various ground wall support systems are as follows (Wilton, 1996):

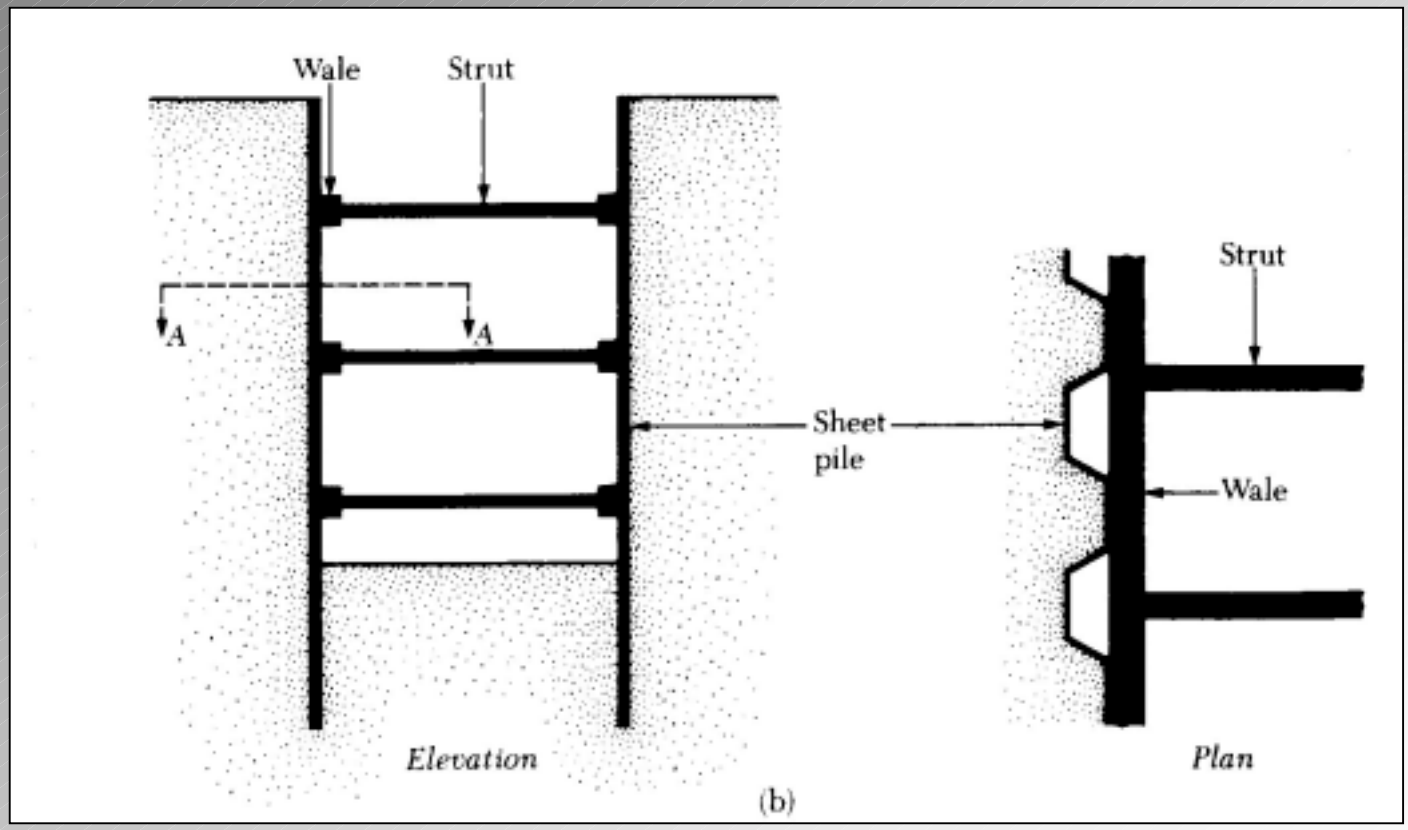
- Soldier piles and lagging: Rolled steel shapes or reinforced concrete piles are used as soldier piles.



Cut and cover tunnels in metropolitan areas

Ground Support Systems

- Steel sheet piles



Cut and cover tunnels in metropolitan areas

Ground Support Systems

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- Closely spaced reinforced concrete piles: Piles that simply touch adjacent piles are called “tangent piles”, those that overlap by drilling part way into the adjacent pile are called “secant piles”.

- Soldier piles with cast in place reinforced concrete

- Shotcrete walls

- Cast in place reinforced concrete slurry wall

- Precast concrete segments placed in slurry trench

Ground Support Systems

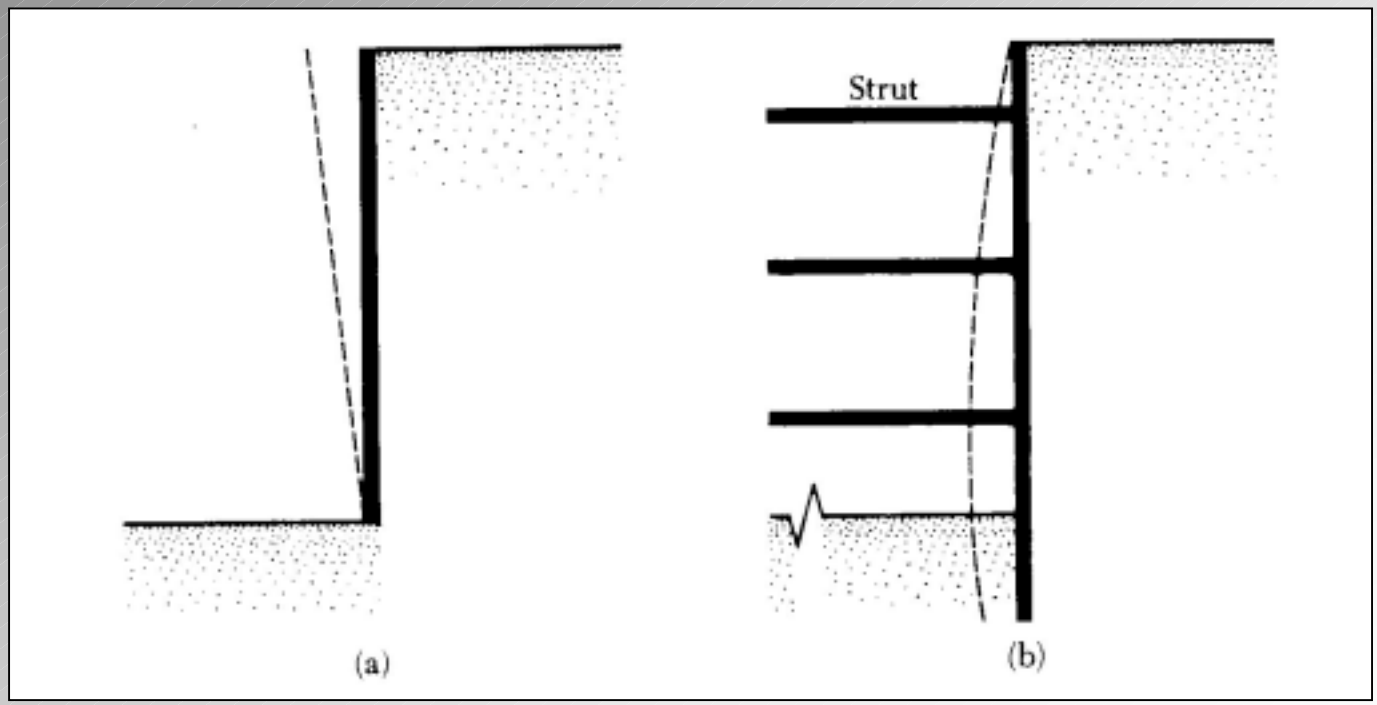
Type of Bracing Systems

Several types of bracing systems are in use today. The choice of bracing is closely related to ground wall support, excavation and construction of the permanent structure.

- Conventional wales and struts: This is an internal bracing system
- Tiebacks and ground anchors
- Combined systems

Lateral Earth Pressures

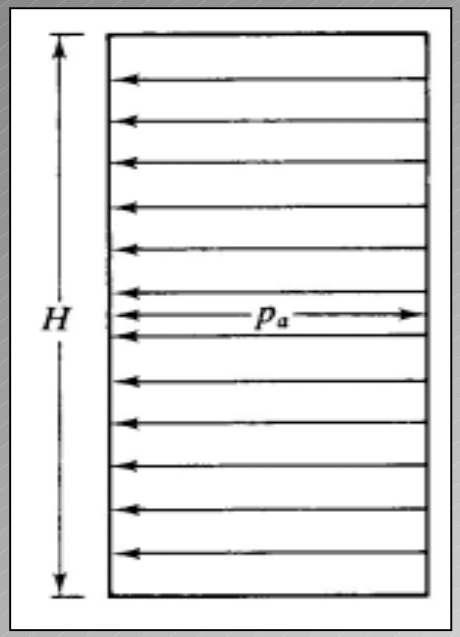
A conventional retaining wall rotates about its bottom. For this case, the lateral earth pressure is equal to that obtained by Rankine's theory. In contrast to retaining walls, braced cuts show a different type of wall movement.



Cut and cover tunnels in metropolitan areas

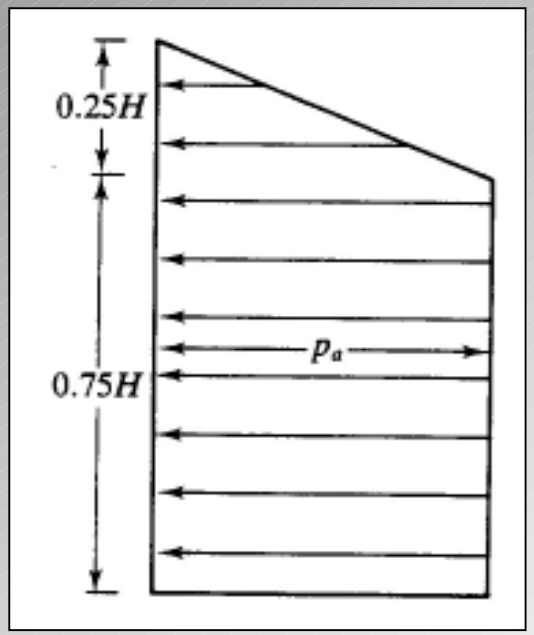
Lateral Earth Pressures

Peck (1969) suggested using design pressure envelopes for braced cuts in sand and clay.



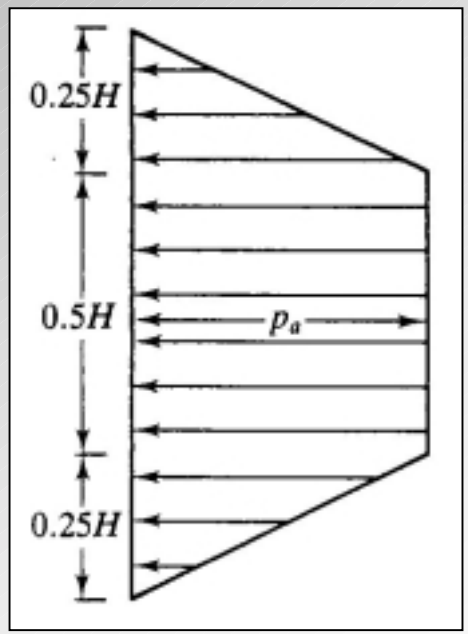
Sand

$$p_a = 0.65\gamma H K_a$$



Soft-Medium Clay

$$p_a = \gamma H\left[1-\left(\frac{4c}{\gamma H}\right)\right]$$



Stiff Clay

$$p = 0.2\gamma H \text{ to } 0.4\gamma H$$

Cut and cover tunnels in metropolitan areas

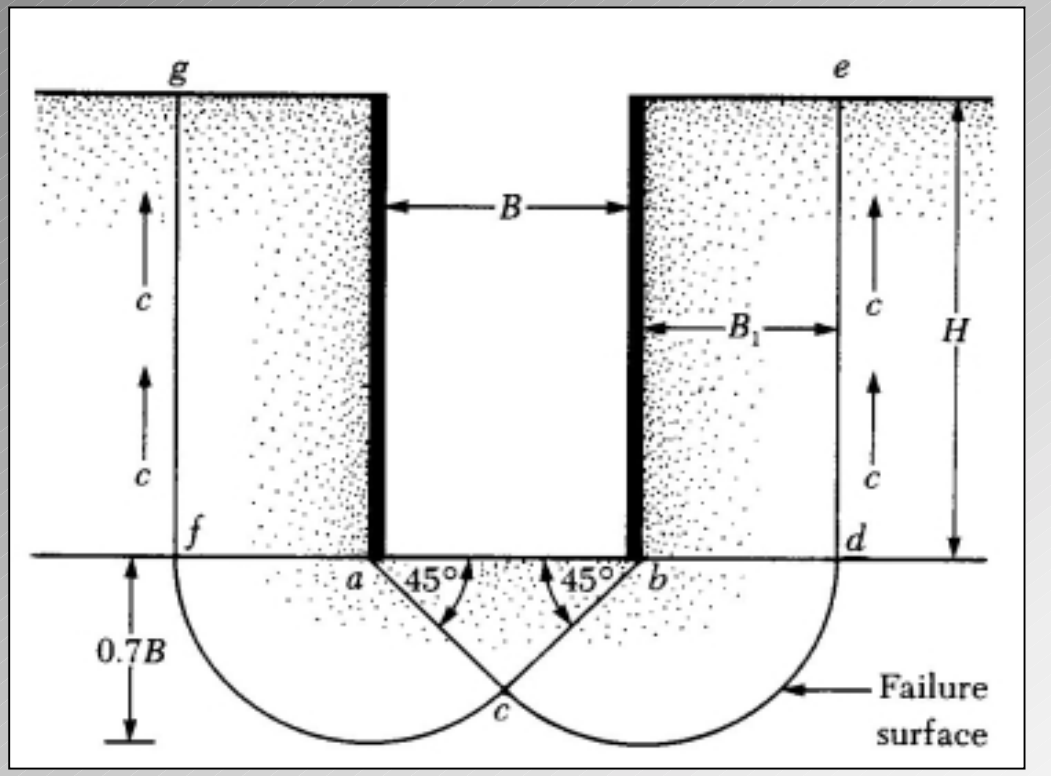
Lateral Earth Pressures

Limitations for the Pressure Envelopes

- The pressure envelopes are sometimes referred to as apparent pressure envelopes. The actual pressure distribution is a function of the construction sequence and the relative flexibility of the wall.
- They apply excavations having depths greater than about 6 m.
- They are based on the assumption that the water table is below the bottom of the cut.
- Sand is assumed to be drained with zero pore water pressure.
- Clay is assumed to be undrained and pore water pressure is not considered.

Base Stability

Heave of the Bottom of Braced Cut in Clay

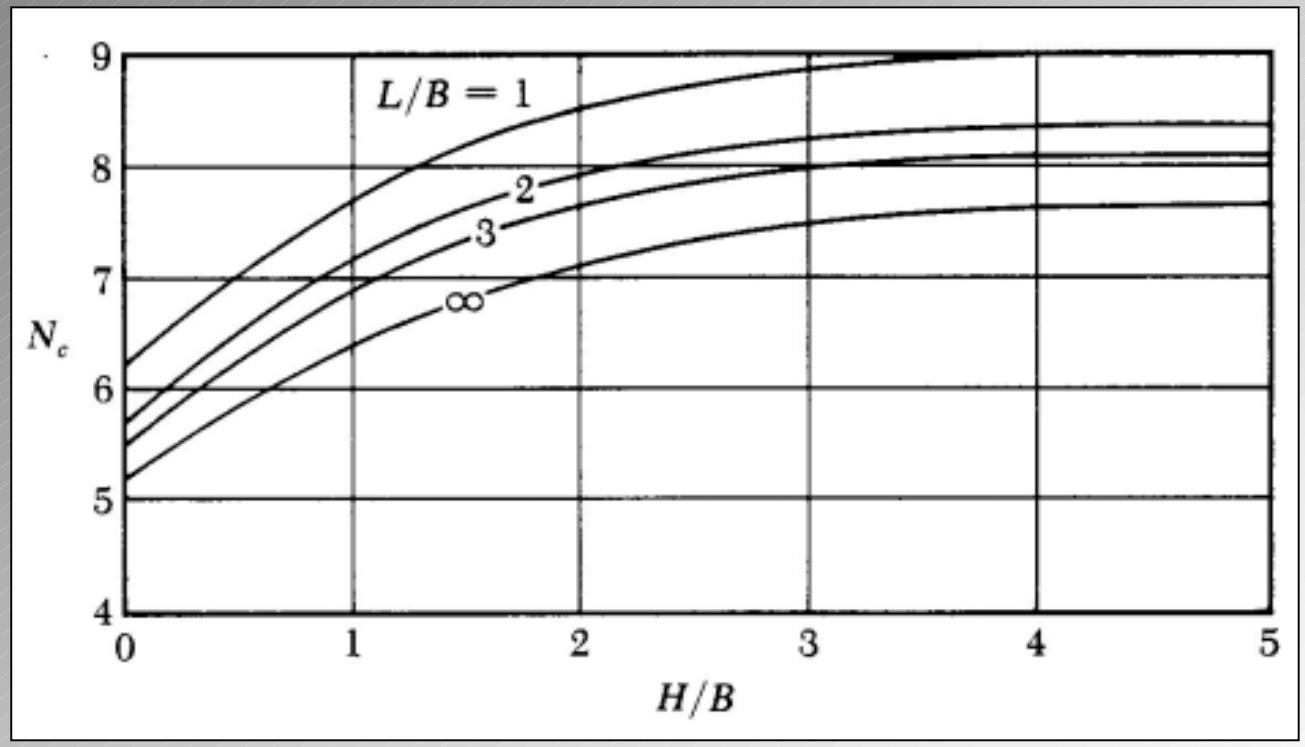


$$FS = \frac{Q_u}{Q} = \frac{5.7cB_1}{\gamma HB_1 - cH}$$

Terzaghi (1943)

Base Stability

Heave of the Bottom of Braced Cut in Clay

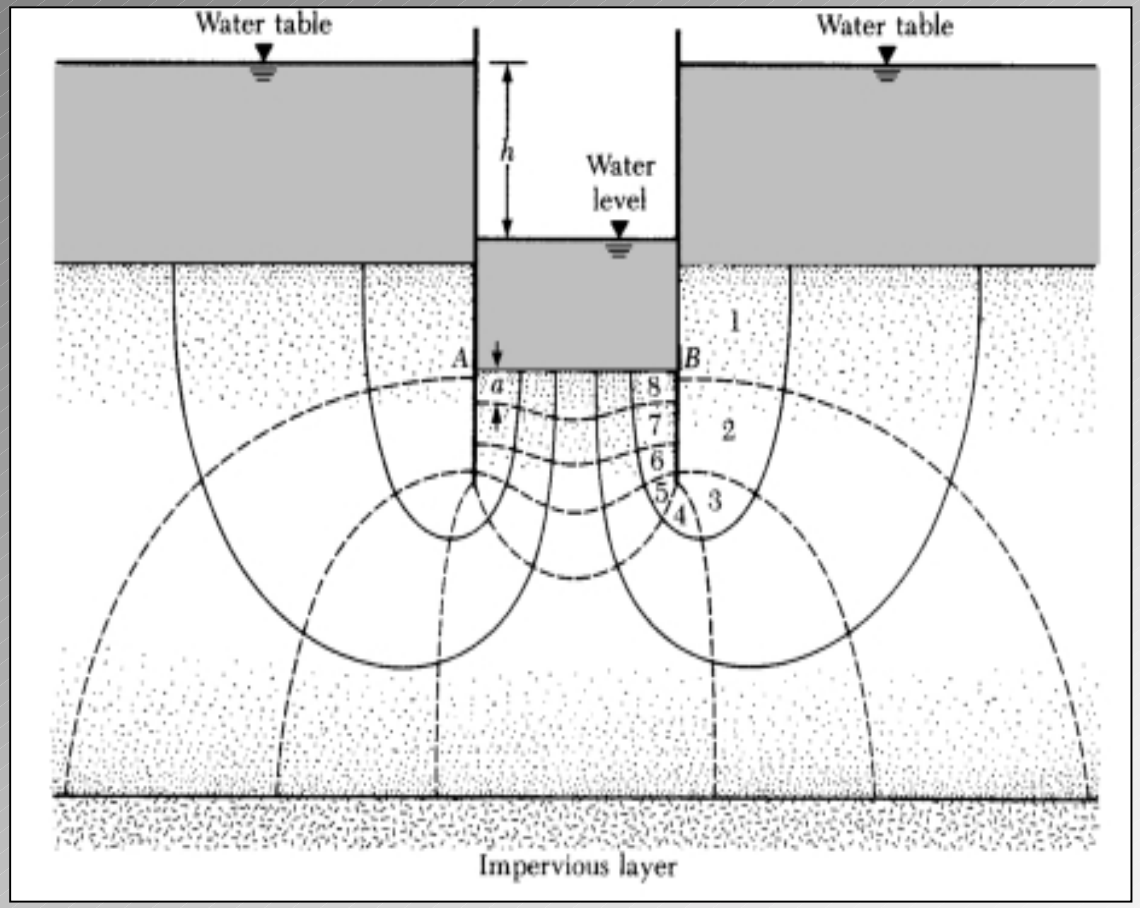


$$FS = \frac{cN_c}{\gamma H}$$

Bjerrum and Eide (1956)

Base Stability

Stability of the Bottom of a Braced Cut in Sand



$$i_{\max(exit)} = \frac{h}{N_d a}$$

$$i_{cr} = \frac{G_s - 1}{e + 1}$$

$$FS = \frac{i_{cr}}{i_{\max(exit)}}$$

Ground Settlement

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The amount of lateral yield depends on several factors, the most important of which is the elapsed time between excavation and placement of wales and struts.

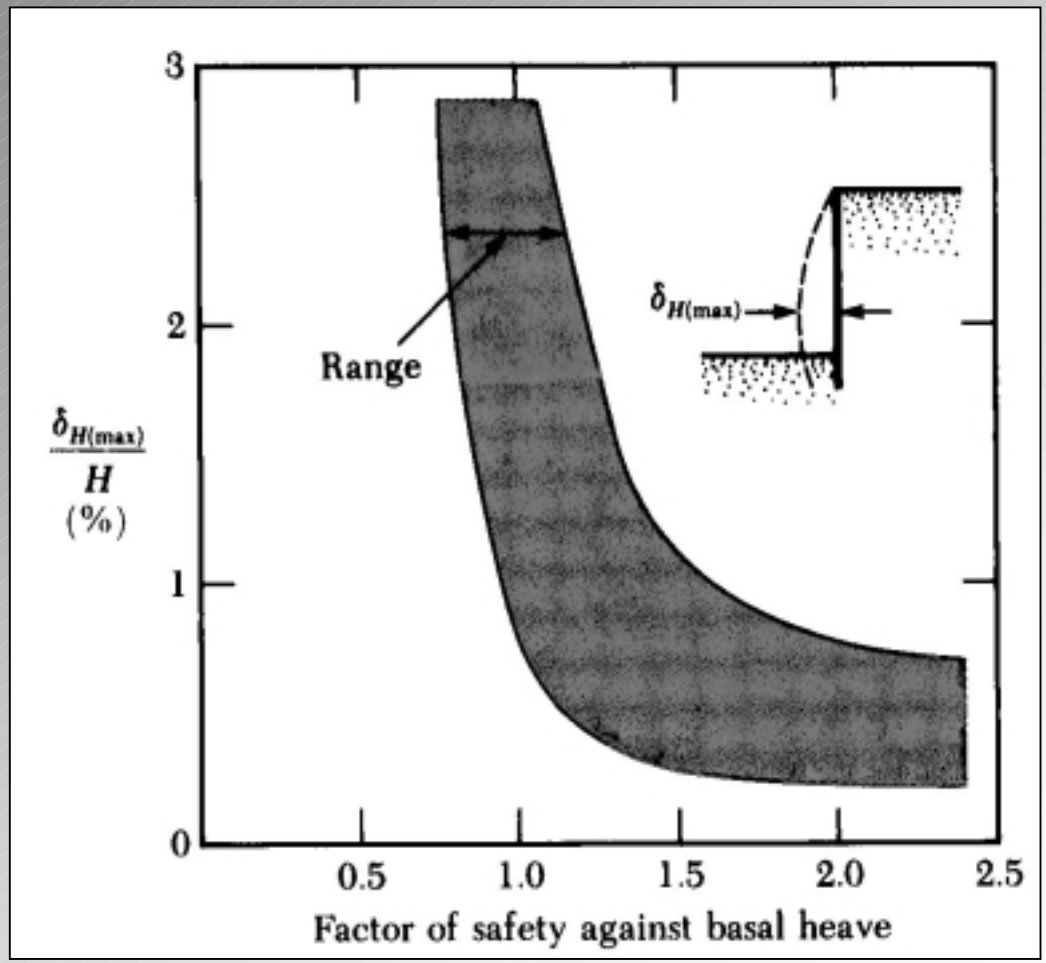
Lateral yielding of the walls will cause the ground surface surrounding the cut to settle.

The degree of lateral yielding, however, depends mostly on the soil type below the bottom of the cut.

If a hard soil layer lies below a clay layer at the bottom of the cut, the piles should be embedded in the stiffer layer. This action will greatly reduce lateral yield.

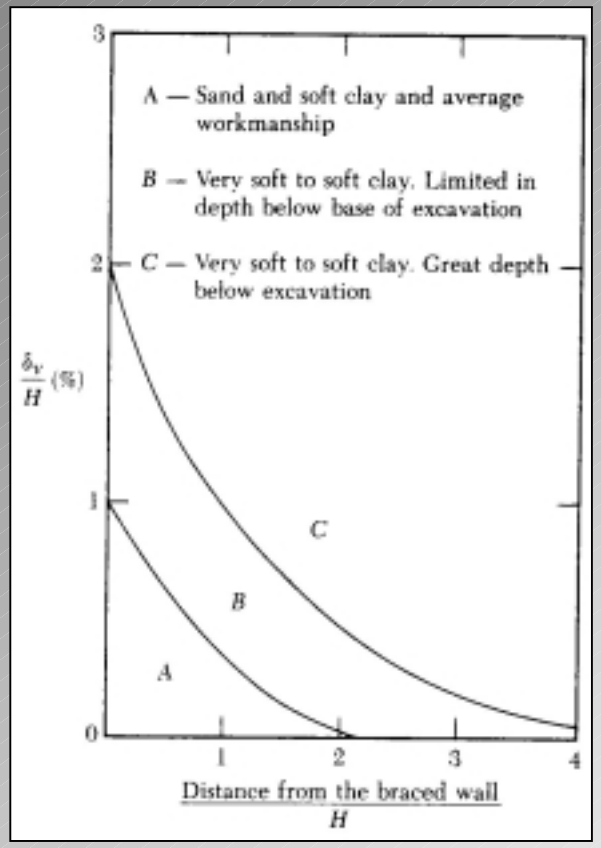
Ground Settlement

The maximum lateral wall displacement $\delta_{H(rnax)}$, has a definite relationship with the factor of safety against heave

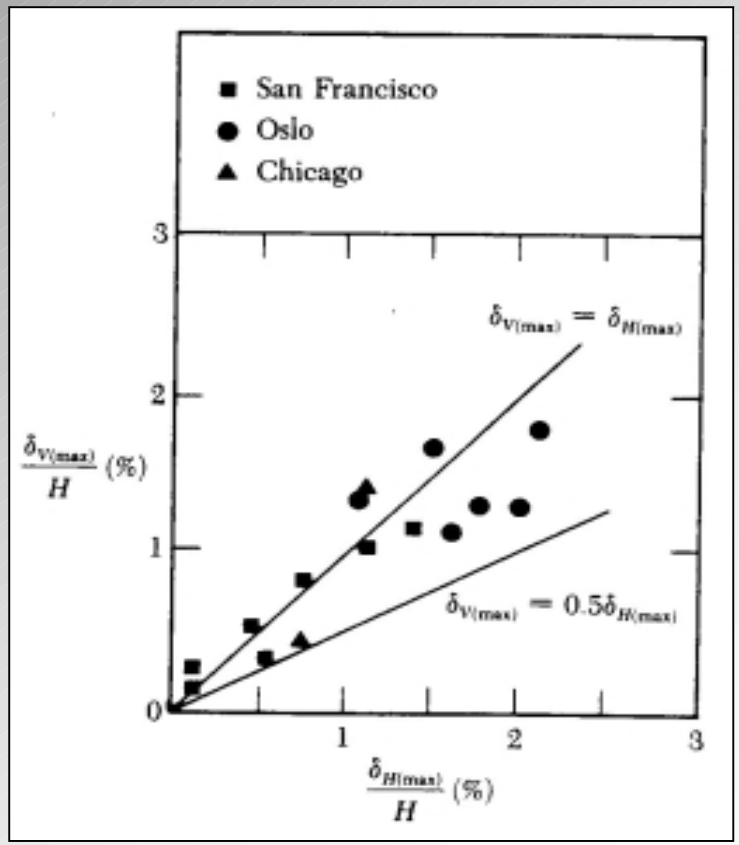


Ground Settlement

The lateral yielding of walls will generally induce ground settlement, δ_V, around a braced cut



Variation of ground settlement with distance (Peck, 1969)



Variation lateral yield with ground settlement (Mana and Clough, 1981)

Case Study: Izmir Light Railway System

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IZRAY is a major component of Izmir Master Transportation System that will consist of 45 km long high capacity railway system when completed.

The first phase of this project that is 11.6 km long has already been constructed between Ucyol and Bornova stations.

There are 10 stations in the first phase of the project. Three of these are underground stations, two of them are on viaducts and remaining are on-grade stations.

Case Study: Izmir Light Railway System

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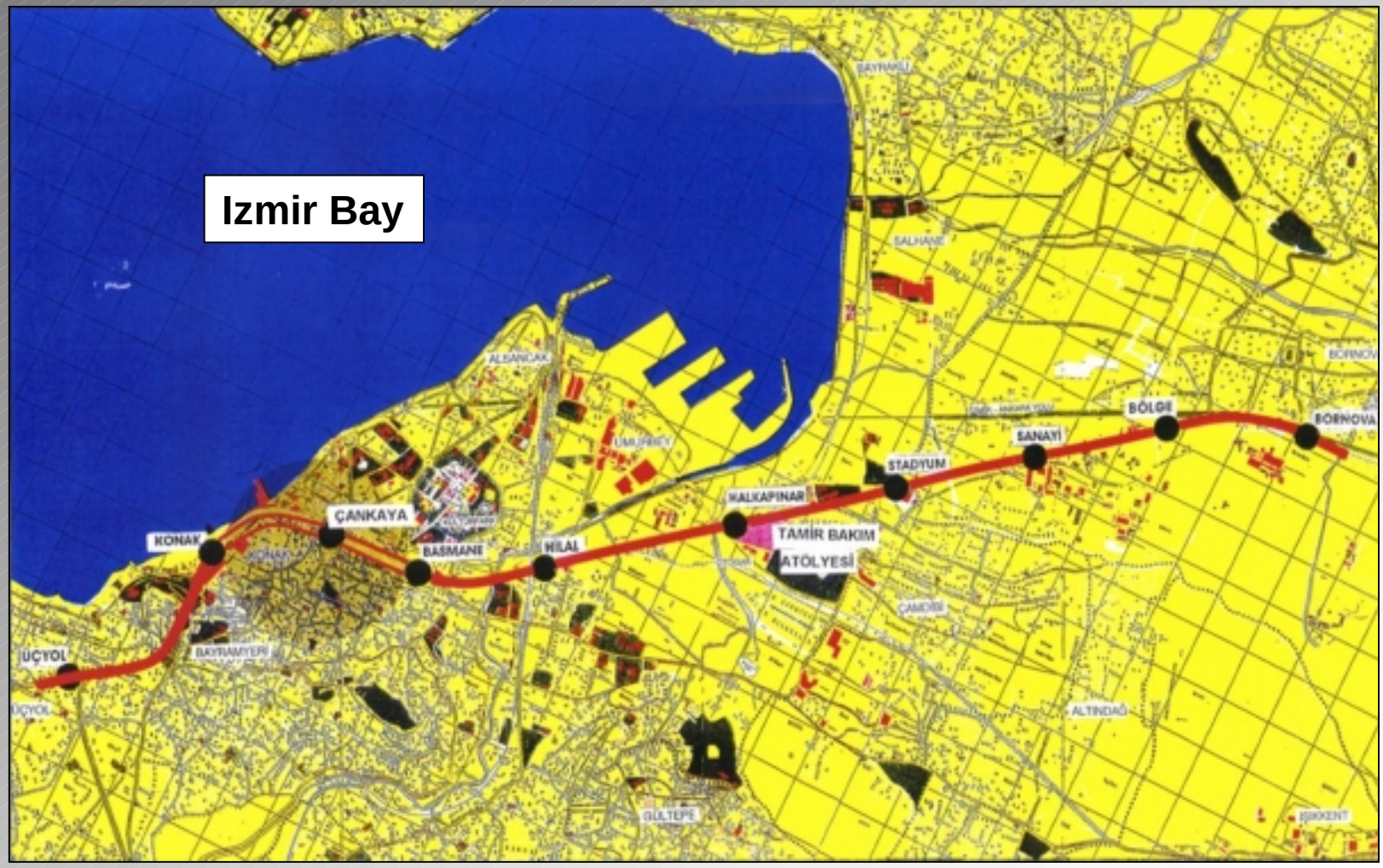

Cut and cover tunnels in metropolitan areas

Case Study: Izmir Light Railway System

1.7 km long twin tunnels between Ucyol and Bahribaba were drilled in andesite rock, utilizing NATM Method. Each tunnel has a 70m^2 cross-section.

These tunnels are followed by Konak Station, which is a 410 m long cut-and-cover structure.

After Konak Station, light railway system continues in 2800 m long twin tunnels that were constructed in soft ground conditions by using EPBM

Case Study: Izmir Light Railway System

Twin Tunnels by EPBM

Cut and cover tunnels in metropolitan areas

Case Study: Izmir Light Railway System

There are cut-and-cover Konak, Cankaya and Basmane Stations, each approximately 200m long and all these underground stations are connected with twin tunnels.

After 553 m long Basmane section, light railway system rests on grade and continues either on grade or on viaduct structures. The light railway system has been in public use since 1998.

Case Study: Izmir Light Railway System

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Soil Profile

There is a heterogeneous man-made fill layer 2.00 m to 6.00 m thick on the ground surface in all borings.

Sea sediments is encountered between 6.00m to 15.00 m depth. These sea deposits are made of alternating layers of medium dense gravel, silty sand and dark gray silty clay having medium consistency.

Neogene aged gravelly clays and gravel bands are encountered below 15.00 m depth. SPT blow counts of the clay layers are in the range of N30 = 14-30 and increases with depth. There are water-bearing layers of sand and gravel with artesian pressure within this clay layer.

The bedrock is Miocene aged andesite. The unweathered bedrock is estimated to be at a depth of 50 to 60m.

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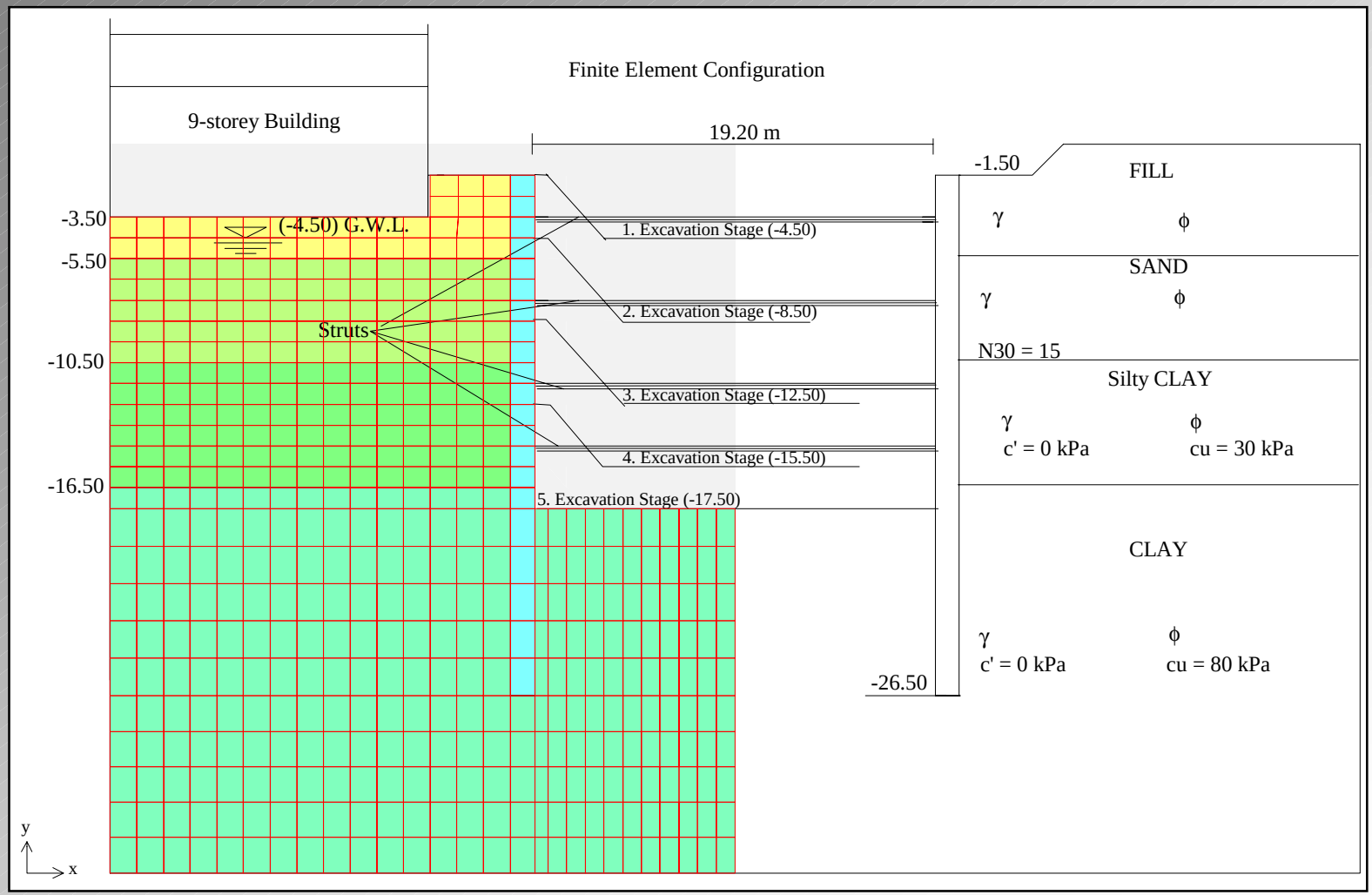
Soil Profile



Cut and cover tunnels in metropolitan areas

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Design of Cut-and-Cover Tunnels

Konak Section (KM 1+550 ~ KM 1+960), which has an excavation depth of 17m, was constructed in a densely populated area next to the historical clock tower of Izmir City.

Cankaya Station (KM 2+708 ~ KM 2+906), which has an excavation depth of approximately 20m, was constructed under Fevzi Pasa Boulevard that is a densely populated business center.

Basmane Station (KM 3+500 ~ KM 4+053), which has an excavation depth of approximately 16m, was constructed next to the historical building of Basmane Railway Station.

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Cut-and-Cover Tunnels

Cut and cover tunnels in metropolitan areas

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Konak Station Diaphragm Wall and Struts

Cut and cover tunnels in metropolitan areas

Case Study: Izmir Light Railway System

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Construction Steps of Cut-and-Cover Structures

An open excavation of up to 2.0 m with sloping faces was carried out as a first step in order to reduce the diaphragm wall height .

Excavation of trenches with bentonite slurry and construction of cast-in-situ reinforced concrete diaphragm walls followed.

Following the construction of diaphragm walls, excavation between the walls was carried out in stages and four rows of steel tubular pipe struts having a diameter of D=800 mm were installed between diaphragm walls.

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Construction Steps of Cut-and-Cover Structures

A horizontal spacing s=4-8 m was used between the struts.

When the excavation bottom was reached, a d=0.75-1.00 m thick reinforced concrete mat foundation was constructed which was followed by the construction of the permanent perimeter walls of the station.

Parallel to the perimeter wall construction, lateral steel struts were removed and waterproofing liner was placed.

Case Study: Izmir Light Railway System

Properties of cut-and-cover tunnels

Station	KM	Exc. width B (m)	Diap. wall thick. b (m)	Diap. wall supported height h (m)	Diap. wall penet. depth D (m)	Diap. wall total height H=h+D (m)	Max. exc. depth (m)
Konak	1+550~1+960	18.80	1.00	15.00	9.00	24.00	17.00
Cankaya	2+708~2+906	19.20~22.25	1.20	14.80~15.60	7.65~8.70	23.00~24.00	20.00
Basmane	3+500~4+053	9.00~18.80	0.60~1.00	3.75~14.20	4.25~9.80	8.00~24.00	16.00

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Design Steps

Engineering behavior of diaphragm walls and adjacent buildings during subsequent excavation stages and seepage into the excavation pits were predicted by utilizing SIGMA/W and SEEP/W finite element software by GEOSLOPE.

Crest deformations of diaphragm walls and corresponding settlements of adjacent buildings were predicted during the design phases. These predicted deformations were compared with measured ones. All measured deformations were within admissible limits.

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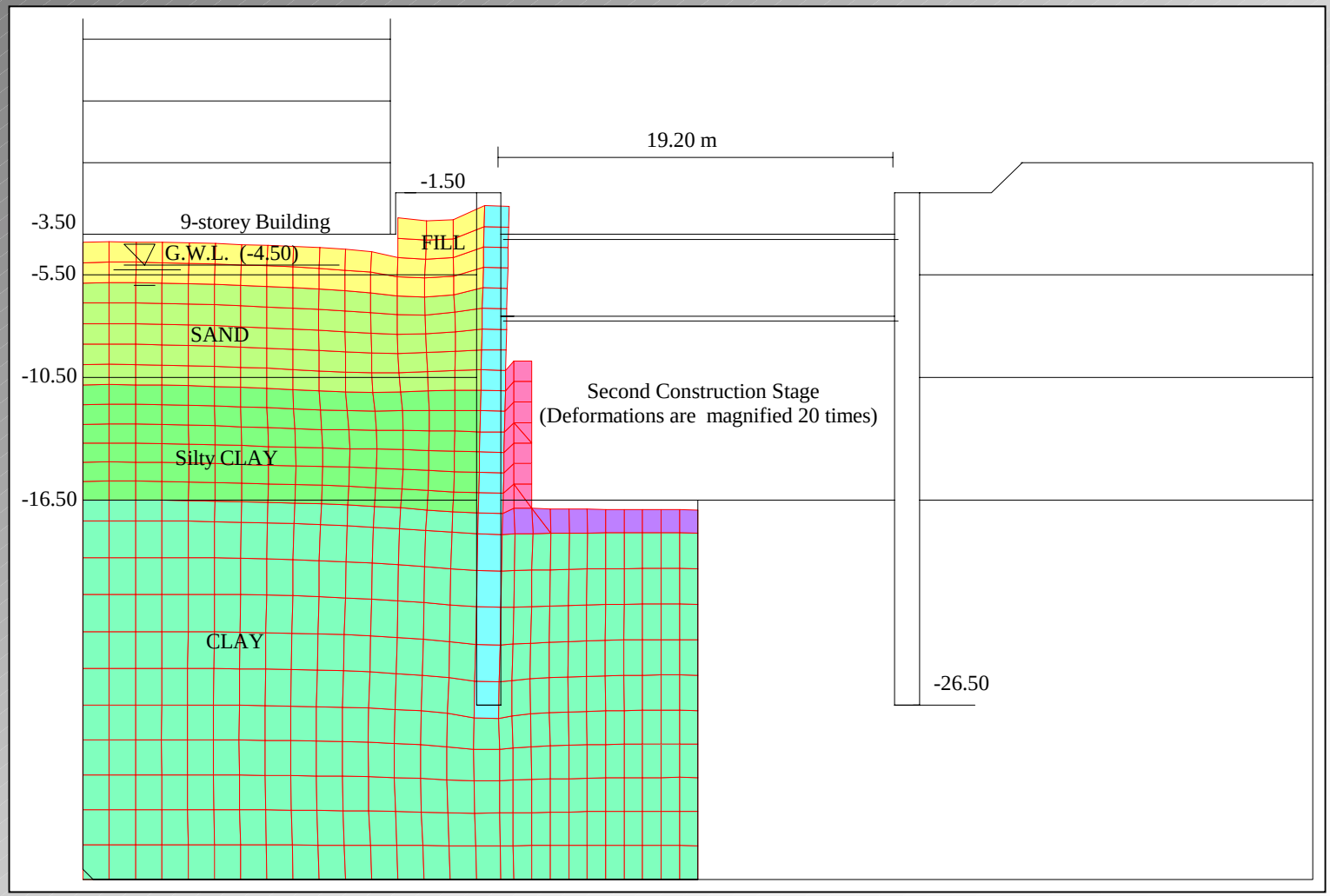
Deformation Mesh for Second Construction Stage



Cut and cover tunnels in metropolitan areas

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Instrumentation

During all construction activities, a detailed field instrumentation program were used to monitor performance of diaphragm walls and neighboring buildings.

Piezometers
Inclinometers
Load-cells on steel struts
Many displacement indicator points most of which were located on the cap beams

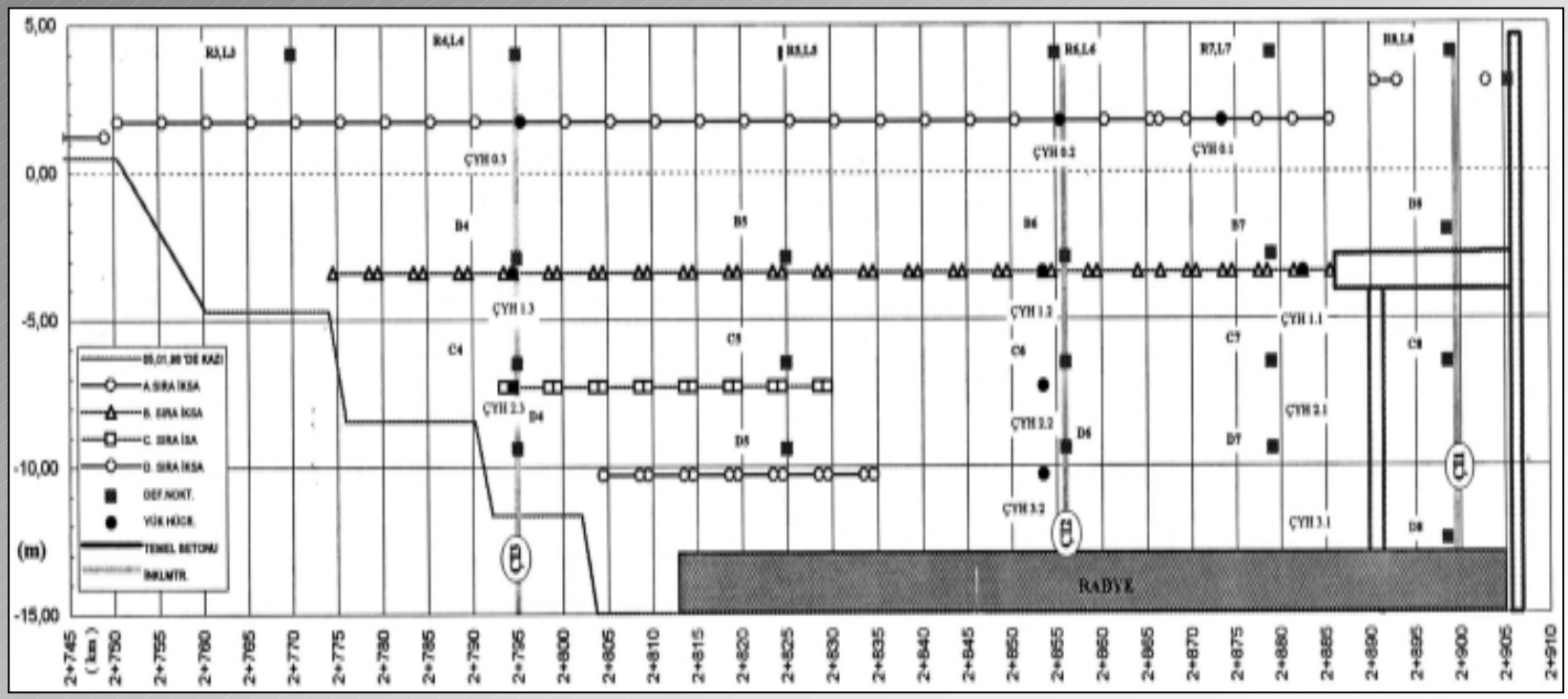
Case Study: Izmir Light Railway System

Summarized monitoring program and geodetic surveying used for the cut-and-cover tunnel structures for three stations.

Station	Number of piezometers	Number of inclinometers	Number of Load-cells	Number of displacement indicator points	
				On struts	On cap beam
Konak	4	4	7	38	12
Cankaya	13	8	16	32	16
Basmane	4	4	13	35	15

Case Study: Izmir Light Railway System

Cankaya Station Excavation Stages and Instrumentation



Cut and cover tunnels in metropolitan areas

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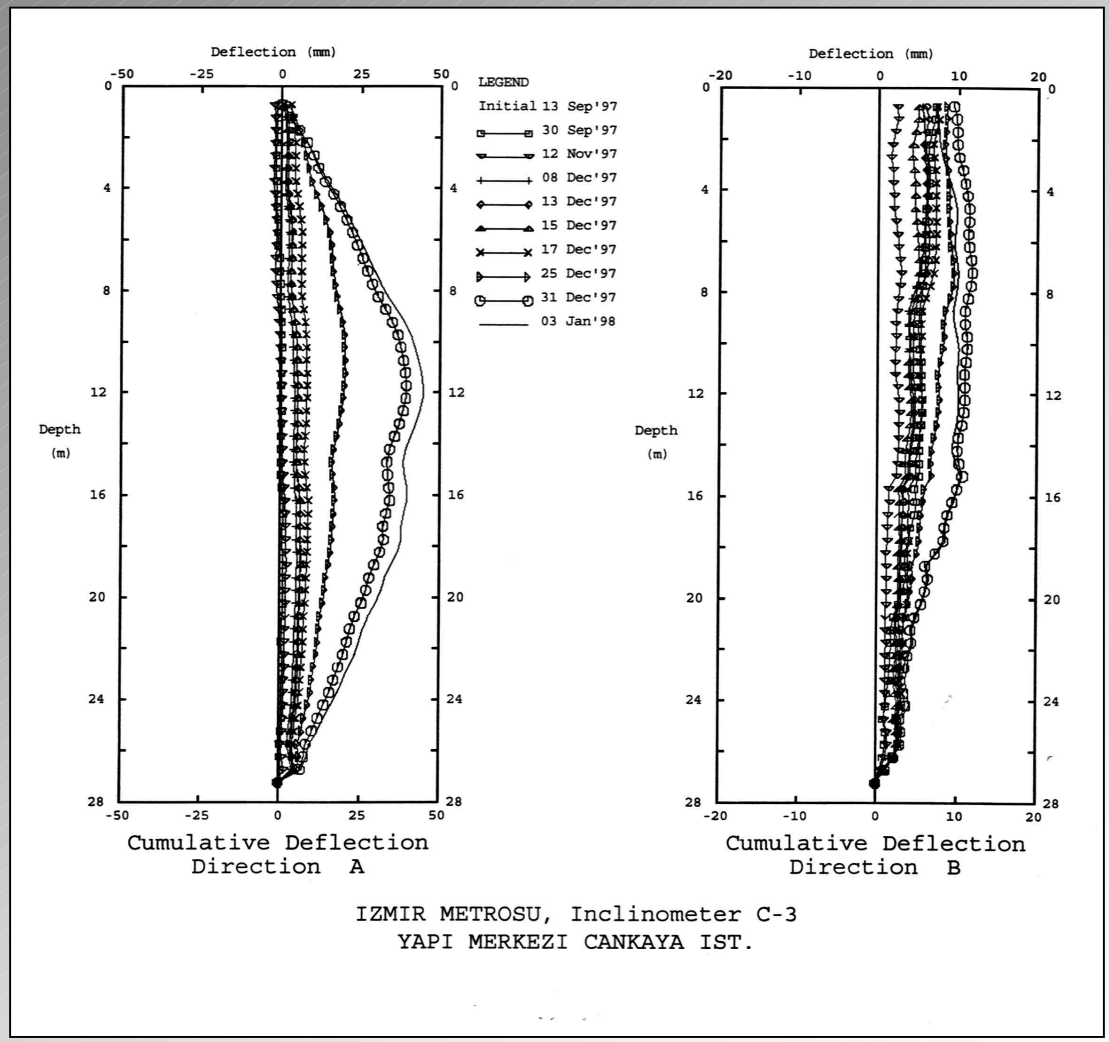
Inclinometer, Cankaya Station



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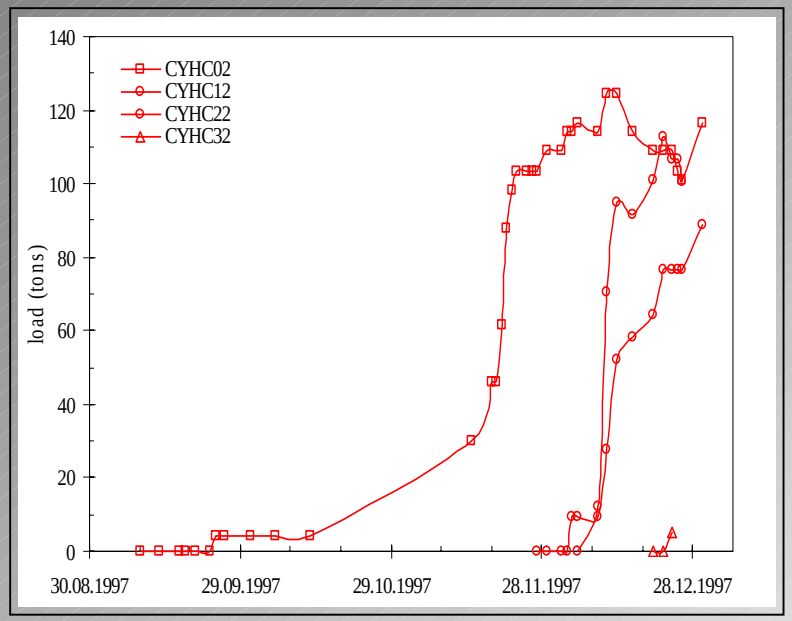
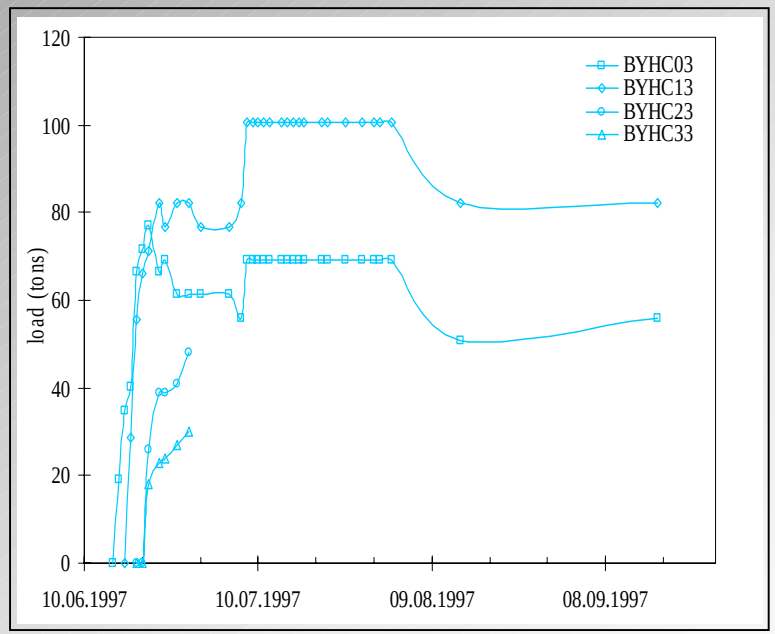
Load Cell Measurements





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Strut spacing for three stations in construction phases

Load-cell readings indicated that first two rows of struts over-loaded when compared with loads predicted in design phase.

On the contrary, load-cells on the final rows of struts those were just above the excavation base indicated very low loads.

Based on these load-cell readings, spacing between struts in each row was re-adjusted.

Following table shows strut spacing for three stations in design and construction phases.

Case Study: Izmir Light Railway System

Strut spacing for three stations in construction phases

Station	Strut Diameter (mm)	Strut*								
			Design phase				Construction phase (revised after design)			
			1. Row	2. Row	3. Row	4. Row	1. Row	2. Row	3. Row	4. Row
Konak	700	Horizontal spacing s (m)	8	4	4	4	*4*	*4*	*4*	*4*
		Number of struts	1	2	2	2	*2*	*2*	*2*	*1*
Cankaya	800	Horizontal spacing s (m)	4	4	4	4	*4*	*4*	*4*	*4*
		Number of struts	1	2	2	2	*2*	*2*	*2*	*1*
Basmane	700	Horizontal spacing s (m)	5	5	5	5	*5*	*5*	*5*	*5*
		Number of struts	1	1	2	2	*1*	*1*	*1*	*1*

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The struts in the first two rows retain the maximum horizontal load, whereas struts in the fourth row retain very low horizontal loads in the range of 30 tons.

These measured distributions of earth pressure are not in agreement with the theoretical pressure distribution given for multi-propped walls in cohesive and cohesionless soils.

Similar measured values of much lower lateral thrusts than predicted in lower braces are also reported in literature (Xanthakos, 1994). It is believed that this is the composite effect of two factors: (1) bottom support was provided by the passive resistance mobilized by the diaphragm wall embedment in stiff clay and (2) preload applied to the upper supports but not to the lower bracing.

Case Study: Izmir Light Railway System

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Ground Water Ingress During Pit Excavation

Boiling of water at the east corner of the Cankaya Station was observed when the excavation reached its final level at 18.0 m depth on September 23rd, 1997.

Discharge of water into the excavation pit was 45 m3/h, and water rise stopped at a level 8.00 m below the ground surface and an equilibrium condition was reached.

An extensive investigation program including additional borings, piezometers installation in the vicinity of boiling were undertaken to find out the causes of the problem.

Remedial measures were decided and implemented accordingly

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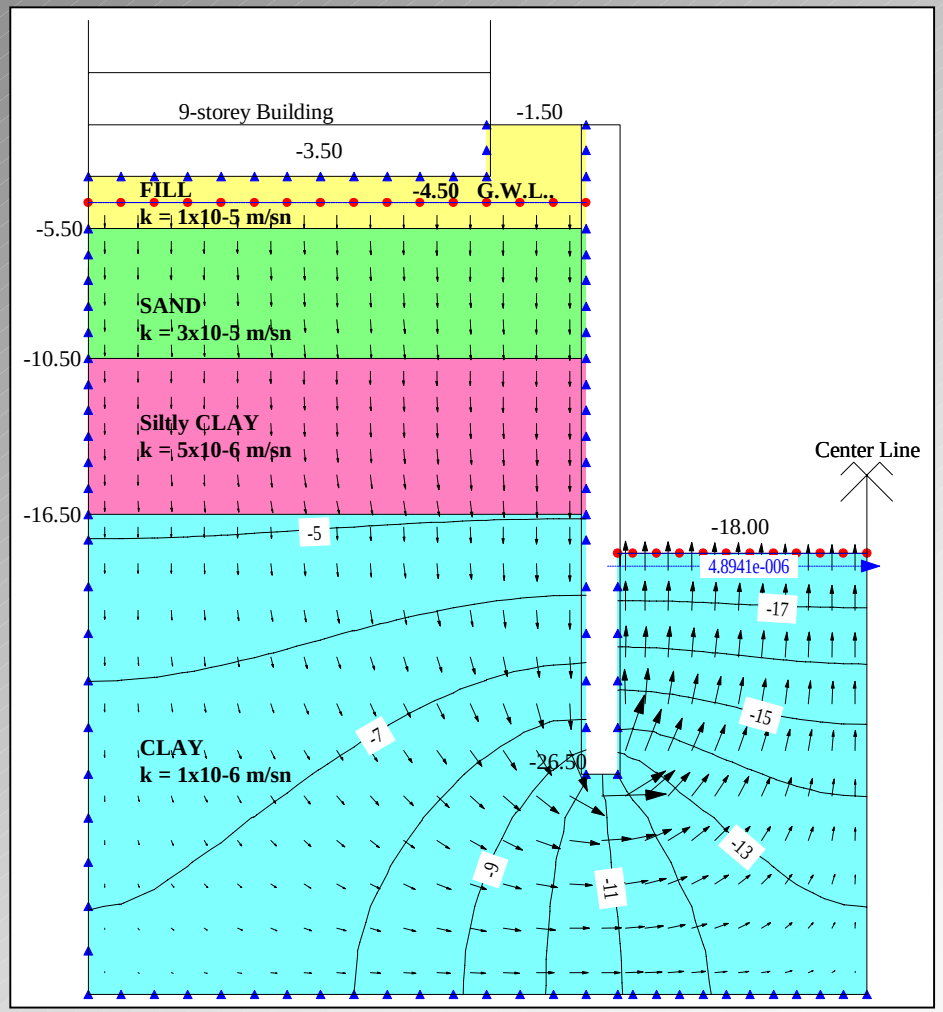
Ground Water Ingress During Pit Excavation



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Ground Water Ingress During Pit Excavation

Cut and cover tunnels in metropolitan areas

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Following remedial measures were considered:

•Cement-bentonite and silica grouting under the diaphragm wall panels at the problem area.

•After grouting has been completed, to pump out the water within the excavation to check success of the grouting.

• As grouting was not successful open relief wells in order to control hydraulic gradient and velocity of the water and dewatering by deep wells that reach to aquifer granular layers.

Case Study: Izmir Light Railway System

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After 1.5 month of extensive soil investigation it was decided to drill three deep wells to stop water ingress.

Three deep wells reaching the aquifer layer, one inside and two outside the excavation pit were drilled and water was pumped out.

This method was successful to lower the ground water below the excavation base.

Pouring of raft foundation at the problem area was successfully carried out in November 1997, practically in dry conditions.

Conclusion

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Cut-and-cover tunneling is a very useful method for shallow tunnels in adverse ground conditions, especially in metropolitan areas. TBMs or EPBMs may also be utilized for these types of tunnels.

Where possible economy dictates that transportation and utilities are placed near to the ground surface and constructed by cut-and-cover techniques.

Principles of the cut-and-cover construction are studied here. A variety of ground support and bracing systems are given. Lateral earth pressures that are exerted on braced cuts, base instability and settlements of nearby structures caused by trenching activities are investigated.
Cut-and-cover tunnels of Izmir Light Rail Project are also reviewed as a case study.

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