Expansive Soil

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Lecture 08
Mechanism of soil-water interaction

Hello everyone, welcome to the course expansive soil. In the last class, we have learned about different type of clay minerals, their formations, their engineering behaviour, and some of the problems related with the expansive soil.

(Refer Slide Time: 00:46)

Next, we will learn about the swelling behaviour of the expansive soil. That means, how a soil swells in presence of the water. In order to understand the swelling behaviour of the expansive soil, we need to understand the mechanism of soil-water interactions, how the water gets adsorbed to the clay surface, so, we will learn on those things in this lecture.

(Refer Slide Time: 01:10)

In this hydration of the clay, the water molecules gets absorbed on the clay surface. So, hydration of a clay can be defined as the mechanism in which the water molecules get adsorbed onto the clay surfaces. Here we can see in this diagram, this is a clay surface, it has negative charge on the surface and there will be some cations which we know as an exchangeable cation, there will be some anions some of there will be some water molecules.

The cations, the anions and the negative charge on the clay surface are responsible for the attraction of the water molecules. So, therefore, the force which responsible for the holding the water molecules generally arises from the clay surface, that is the negative charge of the clay surface, then the cations and the water molecules itself.

Therefore, the force holding the water molecules can be contributed by the clay minerals as well as the water molecules. We will learn how this clay minerals and the water molecules are responsible. So, before going into details, we will see some of the water molecules details. Here you can see this is an example of the water molecules, it is consisting of one oxygen atoms and two hydrogen atoms.

The hydrogens are attached to the oxygen in a V shape and the angle between them is 105 degree and the diameter of this water molecule is around 3 angstroms. Now, the peculiar behaviour of the water molecules is because of its dipole nature. So that means the water molecules have two poles one will be a positive and another one will be a negative. So, because of these positive and negative poles, it will be attracted towards the clay surface as well as it will attract the other water particles.

So, here you can see the edge view of the clay surface, the presence of negative charge over here, and then we have cations, we have the water molecules and these are the anions. So, these water molecules will be attached to the clay surface, because of the hydrogen bonding. Similarly, the cations which are present as an exchangeable cation also absorbs the water molecules and in turn, these are also gets attracted towards that negative plate of the clay particles.

So, therefore, it also brings some amount of water molecules along with them. This process is known as the hydration of the clay or by this process, the water molecules get attached to the clay surface.

(Refer Slide Time: 03:59)

We need to think about how these electrical charges on the clay surface arises. Generally, the negative charge on the clay surface comes from the isomorphous substitutions as well as the broken bond Isomorphous substitution is because of the substitution of an ion by another ion of equal size and lower valency and as a result there will be negative charge.

Similarly, broken bond means the clay particles are continuous in two directions but in third reduction, they gets broken between oxygen and the aluminium atom and because of that, there will be some negative charge on it. If we look into the Kaolinite, Montmorillonite, and Illite; the Kaolinite has a charge of 5 to 15 milliequivalent per 100 grams and mostly the source of this charge is a broken bond.

Similarly, Montmorillonite will have a charge of 80 to 100, that is milliequivalent per 100 grams. And mostly these charges comes from the isomorphous substitutions as well as the broken bond. For illite, it is in between the kaolinite and montmorillonite that is in between 20 to 40. And some of them are comes from the isomorphous substitution and some are from the broken bond.

So, if we compare all these three, Montmorillonite generally poses a large amount of negative charge, therefore, it attracts a large amount of water molecules in comparison to kaolinite and illite. Illite then follow Montmorillonite and Kaolinite will be having a least amount of charge will attract a least amount of water molecules towards it. And generally, this isomorphous substitution takes place during the formation of the minerals.

The positive charge or the hydrogen atoms react with or form a hydrogen bond with the clay surface and as a result, the water molecules will be get attracted. So here in this case, the oxygen atoms, the oxygen and hydroxyl ion of the clay surface will attract the H plus ion of the water molecules and this in turns form the hydrogen bonding, which we will study later on. And then these water molecules again form a hydrogen bonding with another water molecule and this will keep on repeating itself, but the force of attraction will keep on decreasing with the distance.

(Refer Slide Time: 06:36)

Next is a mechanism for soil-water interaction. So, there are a few mechanisms by which the water molecules will be attracted. First mechanism will be the hydrogen bonding. Here we need to understand that the mechanism in which the water gets attracted depends on the mineral surface, that is the surface area, it also depends on the negative charge present in the clay particles and also it depends on types of cations present in the form of exchangeable cations.

First, we will look into the hydrogen bonding. Due to this hydrogen bonding a large amount of water gets attracted towards the clay surface. We know that clay surface has in either a layer of oxygen or hydroxyl present in the clay surface. This is the water molecules. Here, what happens these are the oxygen atoms, oxygen present over here. Now this hydrogen atom forms a hydrogen bonding with this oxygen atoms.

And similarly, there will be also some hydroxyl ion over here, this OH ion, this OH ion will be attracted or will be attached to the oxygen atoms present in the water molecules, thereby, forming the hydrogen bonding here. This hydrogen bonding is generally considered as a secondary valence bond, which we will be discussing later on. And these are the stronger than secondary valence bond but weaker than the primary valence bond.

(Refer Slide Time: 08:20)

Next mechanism is the hydration of the exchangeable cations. We know that there are exchangeable cations present in the clay surface. Now these exchangeable cations will attract the water molecules. Due to the dipolar nature of the water molecules, the negative pole of the water molecules will be attracted towards the cations.

And in consequence again, the positive end of the water dipole again will attract the negative end of the another water dipole. And so, it will keep on in attaching the water molecules like this, but the force of attraction will keep on decreasing with the distance. We will look into the water molecules over here. If this is an exchangeable cation, then it will first attack a few layers of the water molecules and these water molecules will be attracted very strongly.

So, the nature of this water molecules will be immobile, that means it will be not able to move from one position to another points. As we move away from the cations, the force of attraction between the water molecules and the cations will keep on decreasing. So, the force of attraction between cations and the water molecule will decrease and the water will be held lightly.

If you move further away from the cations, so there will be no force of attraction or a minimal force of attraction between cations and water molecules. And the nature of this water will be like a free water, it can move freely from one point to another point. So, this force of attraction of the cations generally comes from the hydration energy of the cations.

Due to this hydrogen energy of the cations, it can attract the water molecules. Higher will be the hydration energy higher amount of water we can attract. If we look into this sodium ion, the size of the sodium ion is around 0.98 angstrom. This is non-hydrated sodium ion, but after the hydration, it can increase its size to 7.8 angstrom. If we look into different types of cations, the size of the hydrated cations can be like for lithium, it can be 7.3 to 10 angstrom.

Similarly, if we look sodium ion, it will be from 5.6 to 7.8 angstrom. And calcium it can be up to 9.6 angstrom, we need to remember one thing the size of the hydrated cations also dependent on the valency, higher will be the valency higher will be the amount of water molecules attached to the cations and the higher will be the size of the hydrated ions.

(Refer Slide Time: 11:25)

The next mechanism by which the water molecules get attracted towards the clay surface is by osmosis. In this process, a large amount of water molecules will be attracted towards the clay particles. If we look into this diagram, this is a clay surface with a negative charge on it, these are the cations and these are the water molecules.

Now, if we look into this diagram, there will be a large amount of cations present next to the clay surface. So, because of this, the concentration of the cations will be quite high next to the clay surface, but as we move away from the clay surface, the concentration of the cation will be decreasing. Now, because of this decrease in the concentration of the cations, there will be a flow of water takes place because of this osmosis.

We can see over here, this is the increase in ion concentration in this direction, because of this concentration gradient, the water molecule will diffuse away towards this and as a result, a large amount of water will be attracted and the water will move in order to equalize the concentration of the cations. So, this is known as osmosis. This process is known as osmosis, and by this process a large amount of water molecules will be attracted towards the clay surface.

So, it also depends on the amount of cations present over here. And it also depends on the concentration of the pore fluid. Generally, the larger amount of cations, then the larger amount of water molecules move due the process of osmosis. So, these are the three different processes by which the water molecules gets attach to the clay surface.

(Refer Slide Time: 13:20)

Next, we will look into the different types of bonds which generally are formed. Generally, the bond which are formed in the clay or clay water system are intramolecular bond and intermolecular bond. The atom can be bound to another atom to form a molecule that is known as intramolecular bond. So, in this case, atom bonding with another atom. So, this is known as intramolecular bond, whereas, in intermolecular bond atom of one molecule bond to atom of another molecule. So, this is known as intermolecular bond.

Intramolecular bond, they are also known as the primary valence bond. Intermolecular bond is known as the secondary valence bond. In primary valence bond or intramolecular bond, consisting of covalent bond, ionic bond, heteropolar bonds, coordinate bond and metallic bond. Whereas, the intermolecular bond consisting of van der Waal bond. hydrogen bond.
Mostly, the primary valence bonds are stronger in comparison to secondary valence bond.

And for any engineering practice, since these bonds are very strong, it is hard to remove in the field. Therefore, the engineers are least concerned about the primary valence bond. Mostly they are concerned about the secondary valence bond because these are weaker bond in comparison to the primary valence bond. So, therefore, we will focus more on the secondary valence bond in this study.

(Refer Slide Time: 14:59)

So, going by the definition. The primary valence bond is the atom bonding to another atom, which is known as primary valence bond. So, examples are the covalent bond and ionic bond. So, these are very strong in nature and seldom broken down in engineering applications.

Therefore, we will not be considering this one.

Whereas, the secondary valence bond, when atoms in one molecule bond to atoms in another molecule, the secondary valence bonds are formed. The secondary valence bonds are London van der Waal's forces also known as van der Waal's forces, and these are intermolecular force of attraction and this bonds acts to a large distance.

Therefore, in clay water system this secondary valence bond plays a very important role. The second type of bond is a hydrogen bond, it is normally considered as a secondary valence bond and but this is stronger than the secondary valence bond, but weaker than the primary valence bond. In hydrogen bond, it occurs when an atom of hydrogen is strongly attracted by two other atoms.

Generally, the example of this hydrogen bond is a water molecule. As I discussed earlier, in a water molecules two hydrogen atoms bonding together with an oxygen atom forming an angle 105 degree and because of this, they form a dipole in which there will be a positive pole and there will be a negative pole. This hydrogen bond is an intermolecular force between the molecules.

And the hydrogen bond occurs when an atom of hydrogen is strongly attracted to two other atoms and, but in this bond the hydrogen cannot decide to which atom it has to bond. So, it will oscillate between them. So, in water molecules, here as I told you, the hydrogen bond forms between the oxygen atoms and it will be attracted towards this, but it cannot decide to which oxygen atom it wants to share its electron. Here you can see, a hydrogen atom is bonding between two oxygen atoms.

(Refer Slide Time: 17:28)

Now, compare the different type of bond in terms of their strength. If we look, the primary valence bond are very strong in nature, generally the bond strength is between 20 to 200 kilo calorie per gram mole. And this acts at a very small distance that is 1 to 2 angstrom. Whereas, the hydrogen bond strength is between 5 to 10.

And it is act to interatomic distance of 2 to 3 angstrom. Whereas, the secondary valence bond is the weakest bond among all this three and generally the strength is between 0.5 to 5 kilocalorie per gram per mole, and it is a long-distance bond and generally it acts at a distance greater than 5 angstrom.

(Refer Slide Time: 18:18)

Apart from this bonding, there are other linkage between the particles and the ions, which can be either positive or negative or that means, either repulsive or attractive. If we look into this, there will be the forces of attraction between the negatively charged soil particles and cations. So, this will be an attractive force.

Similarly, there will be attractive forces between the cations and anions, there will be a repulsive force between the cations, there will be the repulsive ports between the anions. These are the few forces or few bonding which generally takes place in a clay-water system.

(Refer Slide Time: 19:04)

Next, we will discuss about the secondary valence bond. The secondary valence bond is the weakest bond among all, among the primary valence bond and the hydrogen bond. The secondary valence bond is generally due to the presence of the dipole between the molecules. The secondary valence bond is a force between the units of matter arises due to the presence of electrical moment existing between the units. So, this is can be, the example can be like in the form of a magnet.

So, if we bring two magnets, one will be negative charge one will be a positive charge, then the negative and positive charge will be attracting each other. So, similar thing happens in the secondary valence bond, because of the presence of electrical moments, the positive end and the negative end will attract each other, this give rise to the secondary valence bond.

The examples of the secondary valence bond or van der Waal forces, van der Waal London forces which are intermolecular forces of attraction and repulsion. Generally, this secondary valence bonds are attractive in nature. And if we look into this, if in an electrical system, if the center of the positive and negative charge are coinciding together, then there will be no moments or we can say it is a non-polar system.

On the other hand, if it is do not coincide, then there will be moments. Here, we can see some positive ends some negative ends. So, this is known as a polar system or dipolar system, as we talked earlier the example is the water molecules. The water molecules is not electrically symmetrical, here we can see in this diagram, and the hydrogen oxygen hydrogen bonds forms an angle 105 degree and because of this, there will be a positive and negative end of the water molecules.

So, this will be a dipole or the water molecules are known as dipolar. And this secondary bond generally are responsible for holding the water molecules together in comparison to other bonding in a clay-water system.

(Refer Slide Time: 21:36)

Here we will learn about what are the different effect which are responsible for the development of secondary valence bond. The first one is orientation effect. In this orientation effect, there will be attraction between the negative charge and positive charge of the permanent dipole will take place because of the orientation of the dipole.

Here you can see, this is the positive end of the dipole and the negative end of the dipole. The negative end will attract the positive end of another dipole. So, there will be a force of attraction between them. Similarly, in this orientation wise, there will be the positive end and the negative end will be attracted, the positive and negative end will be attracted. Because of this orientation of this particles. So, there will be an attraction between these dipoles.

And we need to remember one thing the position or the orientation of the dipoles get disturbed due to the thermal agitation. That means, if we increase the temperature, then the orientation of the dipole will get disturbed, and so, the effect will also get disturbed. The second one is induction effect, when a non-polar molecule is placed in an electric field is slight displacement of electron and nuclei takes place and the molecule will behave as a polar molecule.

So, when a non-polar molecule is placed in an electric field, a slight displacement of electrons and nuclei takes place and the molecule will behave as a polar molecule. So, this is known as induction effect and this induction effect is marginally affected by the temperature.

The third one is the dispersion effect. Due to the constant vibration of the electrons result in a displacement between the electrons and the nuclei, this displacement results in a temporary dipole which makes the intermolecular attractive forces possible and generally this is present in all the molecules and also this is independent of the temperature.

If we look into the contribution of all these effects, generally the effect of orientation will be around 77 percent, whereas, the effect of dispersion will be 19 percent and the rest will be the induction effect. So, generally these are the share of different effects on the development of the secondary valance bond. So going by this, orientation produces a larger effect in comparison to dispersion and induction.

(Refer Slide Time: 24:38)

So, if we summarize how the water molecules get attached to the clay surface, generally we have three scenarios. Case A; in case A, the negative end of the clay surface will attract the positive and the water molecules. So, again this water molecule will attach to another water molecules and it will keep on like this.

However, the forces of attraction will keep on decreasing as we move away from the clay plates. So, the case one will be the attraction between the negatively charged face of clay particles and the positive end of the dipoles of the water molecule.

In case B, the cations, which are present as an exchangeable cation will hold water molecules due to the hydrogen energy of this cations. Due to the hydrogen energy these cations will attract the negative end of the water molecules and then this will again attract the other water molecules. So, it will keep on like this.

Third case will be due to the formation of hydrogen bonding between the clay surface and the water molecules. As the clay surface contributes to the hydroxyl and oxygen atoms, this hydroxyl and oxygen will react to the hydrogen or oxygen atoms of the water molecules to form the hydrogen bonding and due to this, there will be layers of water molecules attracted towards the clay surface.

So, these are the three different forces or three different causes which are responsible for the attraction of the water molecules towards the clay surface.

(Refer Slide Time: 26:35)

And we need to remember this one, the primary valence bond and hydrogen bonds are too strong to be broken by stresses. Secondary valence bond acts over a relatively large distance.

(Refer Slide Time: 26:46)

Now, we will discuss about different types of forces of attraction and repulsions which exist in a clay-water system. First, we will go with the forces of attraction. So, a number of phenomena generally are responsible for this existence of forces of attraction and repulsion. Those are the primary valence bond and the secondary valence bond. The forces of attractions mostly contributed in a clay water system by the van der Waals forces of attraction.

van der Waal forces of attractions can be defined as a force of attraction between two uncharged molecules. And generally, these are the short-range attractive forces and inversely proportional to 7th power of the distance. That means, this force is inversely proportional to the 7th power to the distance between them. Generally, this force of attraction is exist because of the formation of dipole.

van der Waal forces occurs due to the fluctuation of the charge density of the particles results in the polarization with a positive charge and another end is a negative charge. Here we can see, this is a molecule with a one positive end and these are the electron clouds. Now, due to the fluctuation of the charge density, it will result in a positive charge at one end and negative charge at the other end.

So, this is known as a fluctuating dipole. Now, this fluctuating dipole induced another dipole to an another molecule. So, this is known as induced dipole. This induced dipole will be formed because of this fluctuating dipoles. And now, this negative end or the positive end of this fluctuating dipole and induced dipole will be attracted. So, this force is known as van der Waal force of attraction.

The nature of this force depend on the distance between the molecules and atoms. If the distance between the two atoms is greater than 6 angstrom, then it will be a weak force of attraction. If the distance between these two are 6 to 4 angstrom, then it will be an attractive force. If it is less than 4 angstrom then it will be a repulsive force. So, this Van der Waal force of attraction can be attractive as well as repulsive.

The characteristics of this are, it is a very weaker bond in comparison to covalent or ionic bond. And this van der Waal force of attractions are generally additive in nature and independent of temperature and this is a short-range force.
(Refer Slide Time: 29:41)

The other type of attractive forces are Coulombic force of attraction that we know that if two oppositely charged particles are there, then there will be a force of attraction. Suppose, if there is a charged particles q_1 and q_2, which are separated by a distance say r.

So, the force of attraction, $F \propto \frac{q_1 q_2}{r^2}$

So, this is a Columbic force of attraction.

Another force of attraction between the water molecules or clay surface or in a clay-water systems is hydrogen bond, which I have discussed earlier. Generally, these are the weak bond.

The another kind of force of attraction takes place between the negatively charged clay surface and the positively charged cations, this is a strong bond and is in the order of 10 to 15 kilocalorie per mole.

(Refer Slide Time: 30:38)

The other kind of attractive forces are the dipole-cation-dipole attraction. Here, this is a one clay surface the negative charge over here that will attract the positive end of the dipole and the negative end of the dipole will attract to another positive end of the dipole like this. And finally, this negative end of the dipole will attract the positive end of the cations. So, this is a dipole-cation-dipole attraction, generally these are weak in nature, but exist to a large distance.

(Refer Slide Time: 31:21)

So, if we take two parallel plates of thickness delta and separated by distance 2d, the attractive forces can be expressed by this equation, where, A value is known as Hamaker constant and is in the order of 10^{-20} joule.

(Refer Slide Time: 31:41)

Generally, all these attractive forces depends on the distance. Depending on what kind of attractive forces the variation will also be different, generally, the ion to ion attractive forces is inversely proportional to square of the distance, ion to dipole is inversely proportional to cube of the distance, ion to neutral symmetrical molecules inversely proportional to 5th power the distance. Permanent dipoles and symmetrical molecules are inversely proportional to 7th power of the distance.

(Refer Slide Time: 32:16)

In addition to the forces of attraction, there will be some forces of repulsion. These repulsive forces can be due to the particle charge. Here, we can see the clay surface the negative

charge, another clay surface there will be a negative charge. So, this negative charge will repel each other. So, this will generally form because of the repulsion of this negative charge.

Similarly, there will be some cations, these cations can repel each other. So, here we can see these other cations which are repelling each other and then they will form like this. So, this is in initial state because of the repulsion they will be displaced to this state. However, these repulsive forces are very weak in nature as the cations moves to a new position because of this repulsion.

And this cation charges may also be entirely balanced by the particles charge. So, in that scenario, there will be no cation-to-cation repulsion. So, generally the contribution from this repulsion will be very minimal in comparison to the particle charge repulsion.

(Refer Slide Time: 33:27)

So, in clay water system there will be the forces of attraction, there will be forces of repulsion. So, in an equilibrium the total forces will be balanced by the forces of repulsion and the forces of attraction or the total force will be equals to the force of repulsion plus the force of attraction.

(Refer Slide Time: 33:50)

Next will be the electrical potential. So, electrical potential generally defined as the work necessary to bring a unit charge from an infinite distance to a point. If we look into this plot, which tells us about the variation of the electrical potential with distance. As we move very close to the plate surface the electrical potential will be significantly higher, but as we move away from the plate, the electrical potential will keep on decreasing.

(Refer Slide Time: 34:23)

Now, if we can compare the repulsion and attraction with the potential energy, we can see the repulsion potential. This is a repulsion potential which decreases with an increase in the distance and this increase will be in exponential rate. Similarly, the attractive potential will also decrease with increasing the square of the distance.

Therefore, A always is larger than R, that means, the attractive force is always larger than repulsive force at any distance. The repulsive forces generally are sensitive to electrolyte concentration, valency and dielectric constant. So, any change in electrolyte concentration, valency, dielectric constant, pH can change the repulsion between the particles. On the other hand, the attractive forces are only sensitive to dielectric constant and pH.

(Refer Slide Time: 35:30)

If we look to the two scenarios in which the attractive and repulsive force exist. So, we have two different scenarios in here, first curve A and curve B. This is the curve representing the attractive forces plus repulsive forces with distance. So, this is a distance. The curve A shows that with increasing the repulsion results in a particle approaching each other, if we look into this and increase in the repulsion result as a particle approach each other.

Due to this repulsion the particles will be in suspension. But, if the particles are forced to cross this hump, then what will happen, the attractive forces will increase and the particles will be in flocculated state. Case B, which is represented by curve B, the attraction between the particles increases as the particle approach each other and the particle will flocculate together and they will settle down.

So, these are the two scenarios. In one scenario, the particle repulsion will be increasing as the particles comes closer, but once it crosses this hump, there will be attraction and the particles will move to a closer state and it will flocculate. On the other hand, for curve B as the particles approach each other, there will be attraction and the particles will coagulate and then flocculate.

So, in this class, we will learn about the different types of forces different types of bonding. Then, how the water gets attracted towards the clay surface, how the repulsive and attractive forces combined together acts and that results in the flocculation and dispersion of the particles. We also learned about different types of attractive forces and repulsive forces and their variation with the distance. In the next class we will learn about how the soil will swell in the presence of water. And also, we will learn about the formation of diffuse double layer in a clay-water system.

(Refer Slide Time: 37:55)

These are the few points which I discussed in today's class.

(Refer Slide Time: 38:38)

These are the few references which are used in preparation of this class. So, thank you for your attention.