Environmental Remediation of Contaminated Sites

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Lecture - 17

Remediation of Contaminated GW
Permeable Reactive Barriers

Hello every one. Again, welcome back to the latest lecture session. Again as is customary let us have a quick recap of what we have been up to, right. So we were discussing relevant aspects with respect to remediation of contaminated groundwater, right. So due to various sources either what do we say spill off let us say a hazardous waste or toxic waste or let us say you know you have what do we say toxic compound sometimes present in the act for itself sometimes as is the case with arsenic and saturate, right.

We have a case where the groundwater is contaminated. And we looked at various cases or not cases pardon me options to remediate this contaminate groundwater and some of them are primarily we looked at containment and pump and treat, right. So then we moved on to the relevant passive technique which is the permeable reactive barrier which is used widely abroad again I would think I say that due to lack of transfer of knowledge let us say maybe and also site conditions that are unique to the Indian context obviously I guess, right.

So it is not as well practice in India yet but again maybe the situation is going to change sooner rather than later. So permeable reactive barriers so let us have a quick look at what they are about.

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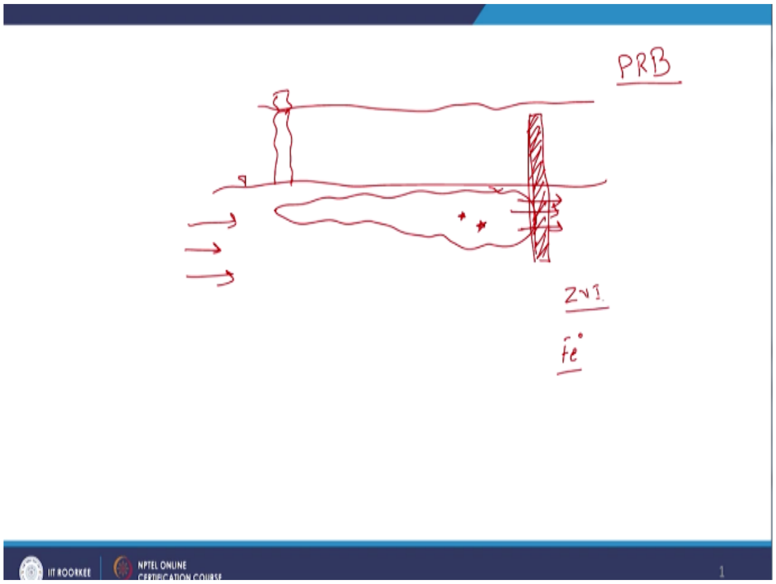

So as we looked at let us say this is the ground surface and I have the contaminated or the contaminant you know there is a release here of the contaminant you know that permeates through the soil and reaches the ground water table and the groundwater is flowing in this direction let us see, so there is particular groundwater is going to come in contact with your hazardous waste here or toxic waste.

And let us say now you have a plume here let us say this is the side view I guess, right. So if it is the side view I should not have had as much vertical dispersion but anyway for purpose of understanding that is fine for now, right. So if we look at pump and treat which was one of the other options we looked at to remediate the containment groundwater we saw that depending upon the type of contaminant especially if it is hydrophobic or non-aqueous or the there is a presence of non-aqueous phase liquid we saw that pumping the water out was not a feasible option, right.

Because you have the contaminant what do we say in the equilibrium between 3 or 4 not 4 pardon me, 3 or 2 different phases. What are the phases? Obviously, groundwater, solid phase or the adsorbed onto the soil and also in the NAPL, right. So obviously we did the relevant calculations and as we saw looked at those cases let us say which in which let us say. The pump and treat is relatively infeasible right. And so we started looking at PRBs what are PRBs. Obviously, Permeable Reactive Barriers, right, permeable reactive barriers.

So typically as we mentioned earlier you know they are constructed subsurface right. This is the side view obviously. And it is permeable though we call that a barrier it is permeable right. And then at the plume let us say is going to now flow through this reactive barrier so you have my reactive media here, I am going to choose my reactive media based upon the relevant contaminant and this particular plume right.

So and then as the we are going to design the relevant PRB in such a way that as the contaminant plume moves through this particular PRB you are going to have the relevant remove for your you know to meet your particular regulations or your design let us see, right. So in this context we looked at relevant aspects and we also mentioned that typically zerovalent iron, zerovalent iron is one of the most widely used the reactive media let us say especially if you have a contaminant that is oxidized, right.

So you have an oxidized contaminant, what does that mean it can accept electrons right. So in that case you need an electron donor which good what do we say example of which is zerovalent iron right. So typically we looked at a few aspects I guess about 0 volatile and what are the different pathways by what zerovalent iron can bring about the relevant removal or degradation of this relevant containment now. So one is the direct path not direct let us see the reduction as in you actually have degradation of the relevant contaminant right.

And the second case was when we looked at let us say reduction and also adsorption onto some of the by-products of this particular iron ore zerovalent iron being oxidized to Fe3+, right. Fe3+ relatively insoluble so it is going to precipitate out so the relevant contaminant can be adsorbed onto this particular Fe3+ precipitate I guess or ferrous iron precipitate pardon me, right. So in that context you would have both reduction and adsorption or you know one but the balance I guess needs to be determined.

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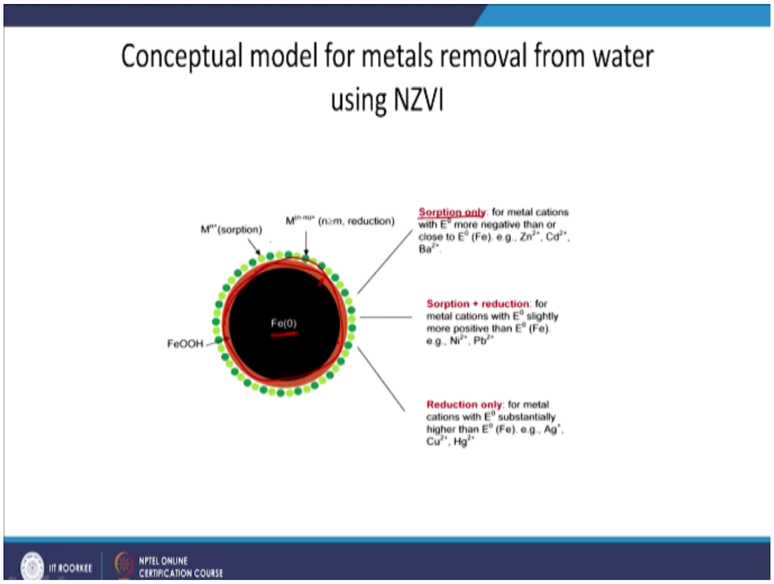

Conceptual model for metals removal from water using NZVI

Sorption only: for metal cations with E^0 more negative than or close to E^0 (Fe). e.g., Zn^{2+}, Cd^{2+}, Ba^{2+}.

Sorption + reduction: for metal cations with E^0 slightly more positive than E^0 (Fe). e.g., Ni^{2+}, Pb^{2+}

Reduction only: for metal cations with E^0 substantially higher than E^0 (Fe). e.g., Ag^{+}, Cu^{2+}, Hg^{2+}

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And third case let us say will have only Sorption, right. And this is the case we looked at so let us say this is your zerovalent iron out here zerovalent iron, so as time progresses let us say you are going to have relevant precipitates on the surface of your particular zerovalent iron, you know I guess they we have a figure here that shows that it is continuous but that will not be the case but you still are going to have as the reaction proceeds what are we going to have you we are going to have Fe not changing to Fe2+ or Fe3+, right.

So once it changes to a Fe3+ let us say, it is going to precipitate out right, Fe3+ does not want to stay in the dissolved phase or the aqueous phase it typically precipitates out. And precipitates out on this particular zerovalent iron site, right. So I guess that is something that we are seeing here. And again you know you are going to now have adsorption of the relevant metal compound or such depending upon the type of compound obviously right. So three cases obviously or three mechanisms pardon me Reduction, Sorption reduction and Sorption only.

So obviously, if we are looking at the relevant aspects with respect to reduction I need to know if the relevant reaction or reduction of the relevant containment is feasible or not. So one way to look at that is PEh0 or P0 Eh0 or such right these are just going to give an idea about the reaction feasibility let us say, right. So I will move on here.

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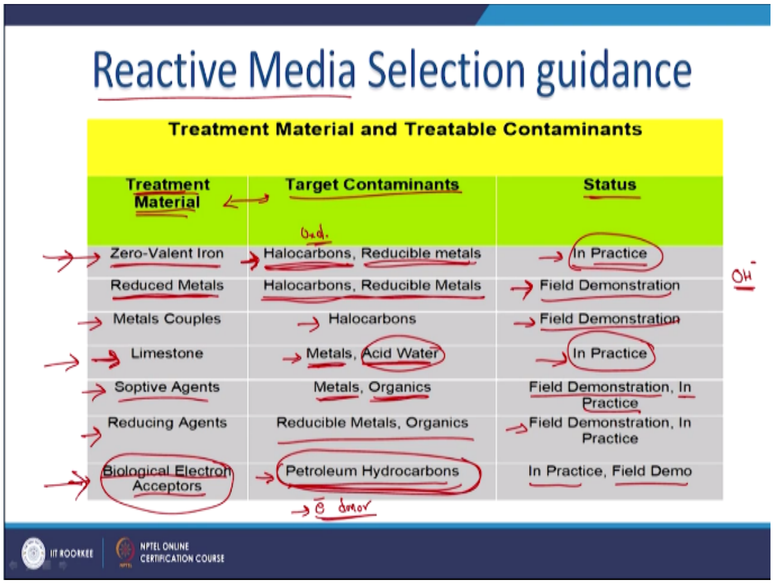

Reactive Media Selection guidance

Treatment Material and Treatable Contaminants

Treatment Material	Target Contaminants	Status
Zero-Valent Iron	Halocarbons, Reducible metals	In Practice
Reduced Metals	Halocarbons, Reducible Metals	Field Demonstration
Metals Couples	Halocarbons	Field Demonstration
Limestone	Metals, Acid Water	In Practice
Soptive Agents	Metals, Organics	Field Demonstration, In Practice
Reducing Agents	Reducible Metals, Organics	Field Demonstration, In Practice
Biological Electron Acceptors	Petroleum Hydrocarbons	In Practice, Field Demo

Oxd.

OH^-

→ $\bar{e}$ donor

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So what are the other reactive media and how can I select them. So these are the treatment materials typically used let us see in this column we have the treatment materials; the typical target contaminants we are going to look at the relationship obviously and then status are in practice or in field demonstration or still in at the laboratory scale; we are going to look at that briefly so that we get you an idea about you know how feasible is a relevant process or mechanism or such let us see.

So as you mentioned zerovalent iron widely used right. So it is a reducing agent, yes, so obviously reducible metals and also hydrocarbons or chlorinated solvents let us say hydrocarbons chlorinated solvents what is the common relevant aspect here that we need to understand that they are oxidized contaminants and you can have reduction of those particular compounds, right.

And again as we mentioned widely practiced and then other reduced metals let us say, again instead of zerovalent iron obviously reduce metals but they might be relatively costlier or have other issues here. Similar to the case of zerovalent iron good what do we see a good example for or good case of being able to reduce oxidized continents so that is what we have here hydrocarbons or Halocarbons pardon me and reducible metals right. Halocarbons are chlorinated solvents good example.

So, but here as you see the feasibility still up in question that is why we still have it what is it mentioned here as field demonstration I guess, right. As in pilot-scale studies have been what we say done but full-scale demonstration or you know not demonstration pardon me they are not yet put into use. So metal couples typically for Halocarbons and again as we see only for field demonstrations, limestone right, and this is an obvious case.

And when are we going to use limestone obviously when we want to what do we say neutralize the water or such let us say right. So obviously good case when one you want to you have acid water or acid mine drainage and let us say one of the aspects you need to control is the pH. So obviously, limestone coming in contact with your acid water let us say is going to help neutralize the relevant what we say plume let us say.

And obviously second case is metals right. And here one aspect is that that we need to understand it metals let us say they can precipitate out, right. So for precipitating out you need a ligand let us say right? And what we say; so here it is a case of metal requiring a ligand right and ligand in this case typically will be either can be over OH- let us say, right and typically when would you get that when you increase the pH and such so that is one particular way to go about that or other aspects and limestone let us say, right.

So in that case again metals can be precipitated out and acid water can be neutralized so again this is in practice right. In practice, zerovalent iron and limestone. So Soptive agents as in those agents that have considerable surface area and would what do we say we amenable to have to provide sites for adsorption for the relevant compounds. So typically organics let us say which are insoluble or would not want to stay in the aqueous phase or in the groundwater.

So let us see now if you have this particular adsorb to agents let us say or Soptive agent the relevant organic compound in the contaminated plume, once it comes in contact with the PRB or the relevant software agent will be adsorbed onto the relevant agent here. And metals let us say they can precipitated out or be adsorbed on the relevant Soptive agent. So depending upon the type obviously I guess we have some in field demonstration some in practice already.

Again reducing agents obviously reducible metals and organics right. And here a relatively unique case as in Biological Electron Acceptors, right. And what is the key here we have the hydrocarbons here, right. And I guess in this case I just need to point something out that I misspelled, here it was not hydrocarbons but Halocarbons.

Chlorinated solvents are such right. Chlorinated solvents obviously are oxidized. Hydrocarbons obviously are reduced, right. So if you already have a reduced form of relevant compound putting in a reducing agent would not work, so obviously that was a misspelled here right. So here it is the oxidized form and here we have the reduced form. So if you have reduced form what does that mean? You have an Electron Donor, right.

So you have an electron donor here, right. So what do you obviously need you need an Electron Acceptor, right. But typically though for petroleum hydrocarbons and such let us say you can try to promote let us say natural attenuation or degradation by microbes present in that particular soil or such but for that obviously how for that particular natural attenuation to work what do you, need you need to be able to promote their particular growth.

And for their growth what do they need they need energy let us say. And how are they going to gain energy now? By promoting relevant redox reactions and what is the redox reactions that they can promote this particular oxidation of petroleum hydrocarbon. But the petroleum hydrocarbon is only an electron donor, right.

For the redox process to go through what else do you need you need an electron acceptor, so in that case the reactive media can be electron acceptor or a biological electron acceptor, right. So again in practice and also in field demo, yes. So a quick recap zerovalent iron good case for oxidized contaminants such as Halocarbons let us say right and reducible metals and then limestone for acid water and metals and then again biological electron acceptors for the reduced compounds which in this case are hydrocarbons, right.

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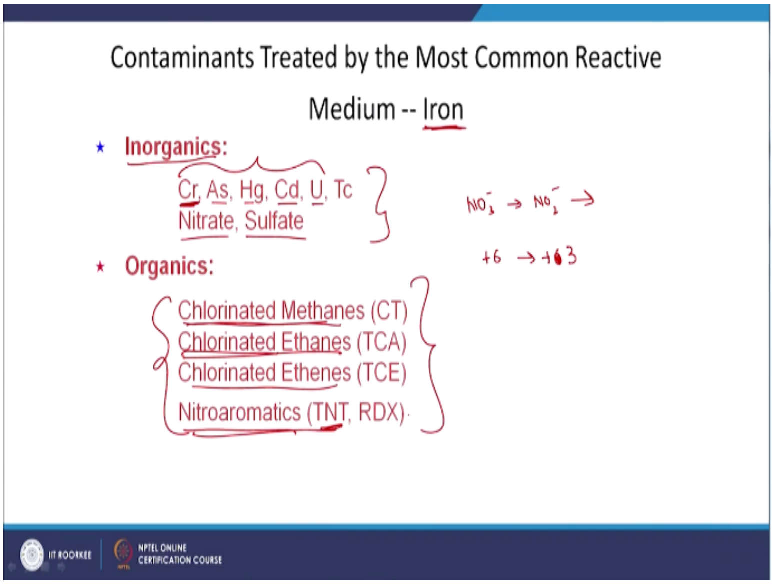

Contaminants Treated by the Most Common Reactive Medium -- Iron

- ★ **Inorganics:**
  - Cr, As, Hg, Cd, U, Tc
  - Nitrate, Sulfate
- ★ **Organics:**
  - Chlorinated Methanes (CT)
  - Chlorinated Ethanes (TCA)
  - Chlorinated Ethenes (TCE)
  - Nitroaromatics (TNT, RDX)

$NO_3^- \to NO_2^- \to$

$+6 \to +3$

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So again let us move forth. So typically again we are going to look at zerovalent iron, again why is that because that is most widely used inorganic let us say chromium, arsenic, mercury, cadmium, uranium and nitrate and sulfite let us say. Nitrate let us say NO3- can be reduced to NO2- and further 2 I guess right. Chromium let us say from +6 oxidation state to + 3, +3 pardon me reduction first and then adsorption let us say or you know chromium in its oxide state of +3 let us say is going to precipitate out.

And again similar cases with most of these such heavy metals here. And Organics obviously what do we see here we see a lot of all our Halocarbons mostly anyway. So Chlorinated compounds here right chlorinated compounds, chlorinated compounds and so on, right. TNT again typically where would we come across TNT or such let us say when you have let us say Army Ammunition dumps are such let us say.

And typically these ammunition dumps are firing rangers let us say that the Army has they have contaminated soil, consumable containment soil because obviously they use the relevant explosives or the relevant area for what we say practice out there right. So obviously you are going to have contaminated soil and also if you have ammunition dumps let us say that have leached or leaked over time that is one popular case when you can have the relevant soil contaminated by the explosives such as nitroaromatic, right.

Again obviously, in such a case let us say where they are remarkably you know what can I say use the term explosive right taking them off to the off-site or treating them and such a relatively expensive option so in that case PRB are you know reducing the relevant compounds by using zerovalent iron zero. PRB is a pretty good way to go about it right. So let us move on; again these are the common what we say contaminants typically reduced by zerovalent iron, right.

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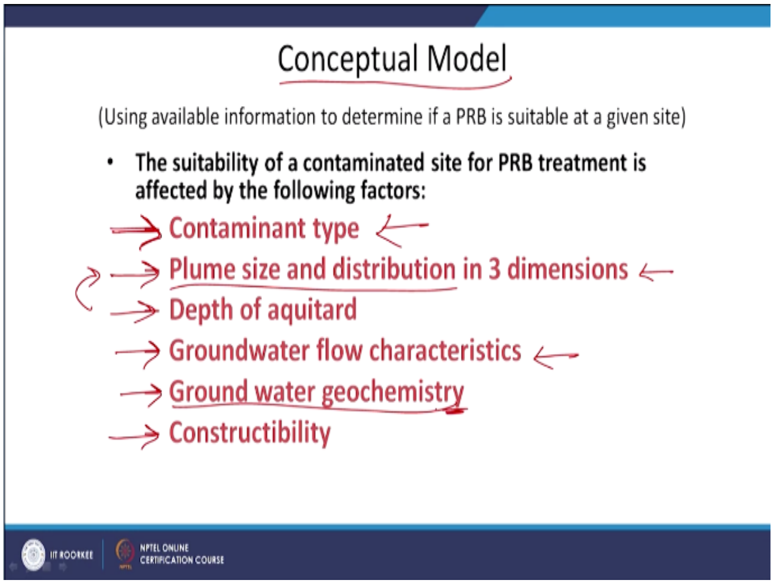

Conceptual Model

(Using available information to determine if a PRB is suitable at a given site)

- The suitability of a contaminated site for PRB treatment is affected by the following factors:
  - Contaminant type
  - Plume size and distribution in 3 dimensions
  - Depth of aquitard
  - Groundwater flow characteristics
  - Ground water geochemistry
  - Constructibility

So moving on; so before we go further though we need to be able to decide let us say given what we say the conditions that we have is PRB feasible or not let us see, so that is what we are going to look at and that is called the Conceptual or developing the conceptual model. For that particular case, what do I need to look at? Obviously, I need to know the containment type let us see, right.

As an, if it is an oxidized contaminant then I will choose the relevant what do we say zerovalent iron or relevant reduced compound or reducing agent to treat my contaminant. So obviously I need an idea about the contaminant type. And the key aspect is to be able to understand the plume size and distribution. For example, the plume size, let us say and the distribution in such a way that it has spread or a large extent of area let us say, right write and then it does not make sense obviously or it is not feasible to be able to treat that particular plume.

At least at the relevant periphery survey, you can have it at maybe midway or such or you know at strategic locations let us say. But you know when the plume size and distribution is way too large you know sometimes PRB is not sometimes PRB might be infeasible right. And also let us say a plume size and distribution is important because obviously you need to know where to place it, what is the width of my PRB right, what is the depth of my PRB and so on.

So typically let us say in those cases where the PRB installations have failed it was not because of let us say the PRB failing due to the technical deficiencies but because the plume size and distribution and many deviations from the estimated distribution were not looked at stringently let us say. Again the plume size and distribution was not what we see accurately looked at and thus people had issues with PRB failing why is that because the contaminant plume did not go through the PRB but went around the PRB, right.

Again depth of aquitard are the relevant impermeable layer right that will give an idea about again the depth to which your particular PRB needs to install, to be installed; again relevant also to the plume size and distribution. Groundwater flow characteristics right. Obviously, you need to know the hydraulic conductivity and the relevant velocity and such groundwater flow characteristics pardon me and groundwater geochemistry as in; are there any other compounds in that particular relevant aquifer let us say, that can either aid or hinder the relevant reactions that would be promoted in PRB.

For example, you have zerovalent iron let us say and you have water that what we see has consumable dissolved oxygen let us say, right. So what is going to happen here your water would react with the zerovalent iron or water which is an electron; not water pardon me the oxygen which is an Electron acceptor, it will react with zerovalent iron which is an electron donor, right.

So what does that mean let us say the relevant kinetics of your particular reaction or the number of sites available for your particular reaction let us say were zerovalent iron degrades the relevant contaminant are going to be lesser, right. So in such cases obviously you want to look at groundwater geochemistry. And also let us say with respect to Constructability as in what is the feasibility let us say with which you know at given that particular aquifer characteristics and also the depth at which you need to construct it and the kind of PRB that would be suitable; can I construct that yes or no, so these are the aspects obviously, right.

But typically the plume size and distribution, groundwater flow characteristics contaminate type and I guess to some extent groundwater geochemistry that we look at, at this stage now, right.

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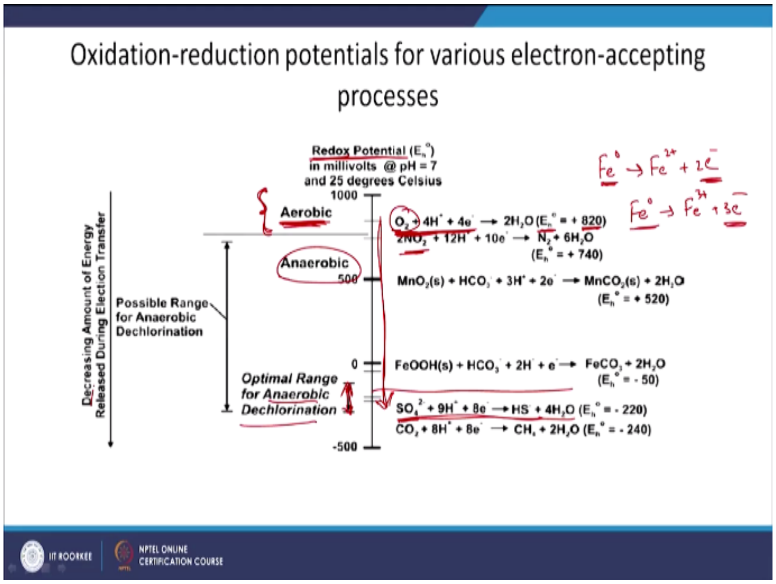

Oxidation-reduction potentials for various electron-accepting processes

Redox Potential (E_h°) in millivolts @ pH = 7 and 25 degrees Celsius

1000

500

0

-500

Aerobic

Anaerobic

Decreasing Amount of Energy Released During Election Transfer

Possible Range for Anaerobic Dechlorination

Optimal Range for Anaerobic Dechlorination

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (E_h° = + 820)

$2NO_3^- + 12H^+ + 10e^- \rightarrow N_2 + 6H_2O$ (E_h° = + 740)

$MnO_2(s) + HCO_3^- + 3H^+ + 2e^- \rightarrow MnCO_3(s) + 2H_2O$ (E_h° = + 520)

$FeOOH(s) + HCO_3^- + 2H^+ + e^- \rightarrow FeCO_3 + 2H_2O$ (E_h° = - 50)

$SO_4^{2-} + 9H^+ + 8e^- \rightarrow HS^- + 4H_2O$ (E_h° = - 220)

$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$ (E_h° = - 240)

$Fe^0 \rightarrow Fe^{2+} + 2e^-$

$Fe^0 \rightarrow Fe^{3+} + 3e^-$

So in this case obviously to be able to understand whether it is feasible or not we have the relevant what do you say graph here. So here I have decreasing okay this is not the right way I guess. Okay here I have the redox potential, right. So in one of the earlier cases when we looked at zerovalent iron we looked at what do we see cases where it would work as what we say only a reducing agent and the second case where the process such as adsorption and reduction go hand-in-hand and one case where only sorption would be feasible or such.

So how do I know let us say whether a relevant compound let us say can be reduce by this particular zerovalent iron or not or in which cases will this particular zerovalent iron based PRB you know work well let us see. Obviously, what are some of the; what we see ranges in which it would not work well when you have oxygen here right. So obviously in this zone let us say when you have oxygen obviously you have the relevant Eh0 out here right.

So you see that in this zone obviously it is not going to be feasible out here right. Why is that because obviously you have let us say a relevant compound here somewhere out here. Let me look at this relevant case once. So here we have the Aerobic zone here as an oxygen would act as the electron acceptor as you can see here.

So let us say if Fe0 goes to Fe2+ + 2 electrons or Fe0 goes to Fe3+ + 3 electrons let us say these electrons are going to be preferentially be; what do we say consumed by or accepted by oxygen here, especially obviously as you see that it is an aerobic phase and Eh0 here is > or Fe02 anyway is > that Fe. Let us say the relevant cases were sulfide or sulfate let us say as before 2- is being reduced here.

So what does that mean now let us see. Obviously, you know the relevant reaction that would lead to promotion of typically anyway obviously kinetics is a different aspect; the greater the energy those reactions energy released those reactions would be promoted. So obviously as you see let us see, in this case if you have oxygen as an electron acceptor that would be first compound that will preferentially react with this electron donor, right.

So in this order you have the preference of the relevant electron acceptors, right. So what does that mean so if oxygen is present and let us say SO4 2- is present right which one would react with preferentially with zerovalent iron? Oxygen, yes. So same case with let us say nitrate and so on right nitrite I guess it is nitrite NO2- yes. So here you have the Aerobic zone and Anaerobic zone.

But typically let us say this is the optimal range for Anaerobic Dechlorination, and this is where you get the typically Eh0 values for most of these chlorinated solvents, right. So again the key aspect here is if you have a chlorinated solvent and oxygen at relatively high concentration and you have zerovalent iron so obviously which one would react with zerovalent iron oxygen here, right.

So obviously for optimal removal of these particular chlorinated solvents you need to have or you should not have oxygen right, so or you need to have the optimal anaerobic conditions, so that is what we can see here. Again as I mentioned decreasing amount of energy released during electron transfer, right. So from as I go from here to here decreasing amount of energy is released and one metric or you know an idea would be to look at the redox potential here, right. Again let us move on.

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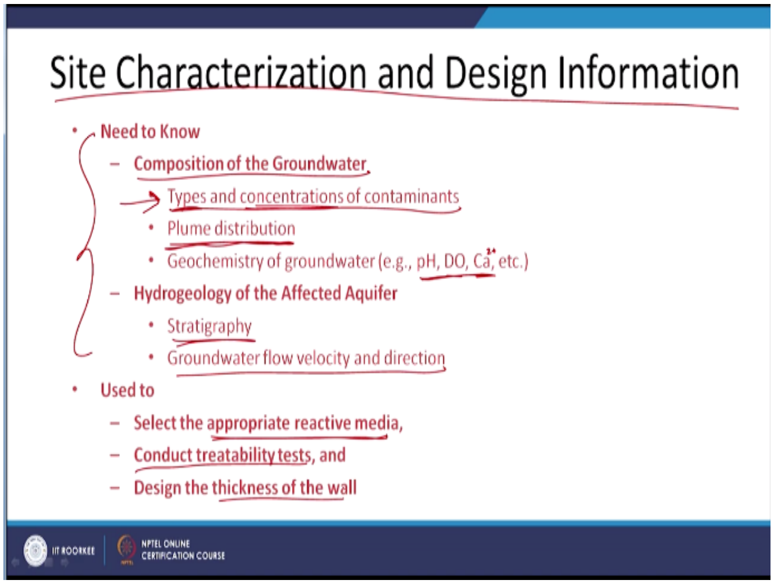

Site Characterization and Design Information

- Need to Know
  - Composition of the Groundwater
    - Types and concentrations of contaminants
    - Plume distribution
    - Geochemistry of groundwater (e.g., pH, DO, Ca^{2+}, etc.)
  - Hydrogeology of the Affected Aquifer
    - Stratigraphy
    - Groundwater flow velocity and direction
- Used to
  - Select the appropriate reactive media,
  - Conduct treatability tests, and
  - Design the thickness of the wall

So Site, once I am done with the conceptual model, site characterization let us see. Now let us say I know that okay it is feasible or you know I have the relevant information primary information preliminary to know that it is feasible or it has in installation of PRB is feasible and now I can put in more resources to understand let us say or do to look into the system in greater detail. So obviously, what do I need to know, I need to know the composition of groundwater as in what are the different contaminants and concentrations of the contaminants, right.

And again plume distribution let us say and with greater accuracy yes, a geochemistry as in pH, dissolved Oxygen, calcium, concentration and so on right and these are the aspects that I am going to look at. And again Stratigraphy I guess, right and groundwater flow velocity and direction. But again these are aspects we considered in the conceptual model but we need them in our, you know in greater detail let us say in this case.

Stratigraphy has and you have different strata right in the case of what do we say pump and treat we looked at stratigraphy too as in we had sand layer, clay layer and so on and so forth. So again the relevant aspects play role here, so you need to look at the stratigraphy here too. And obviously what will this help me with to select the appropriate reactive media as in from this particular case as in types and concentrations of contaminants.

I can select the appropriate reactive media to help me to conduct treatability tests again and then design the thickness of the wall, right. So obviously what am I going to design I am going to look at let us say the length of the PRB and the height of the PRB. But typically that will be determined by the plume size and distribution.

But what will the thickness of the PRB be determined by right; it will be determined by the kinetics as in how fast can the reactive media degrade your particular contaminant that is going to flow through your PRB as in this is the side view and this is my PRB and let us say if I am looking at the concentration profile here let us say right or let me say this is the thickness and the contaminant is coming in and going through and this is concentration on the y-axis and distance our thickness of the PRB here, right.

What would you observe? You would observe profile something like this, right. So by time it reaches the particular outlet of the PRB the concentration typically would be relatively less, so that is my design basically as in how do I end up with calculating the thickness, right. So these are the aspects that you know I need to look at to be able to get my design info, yes.

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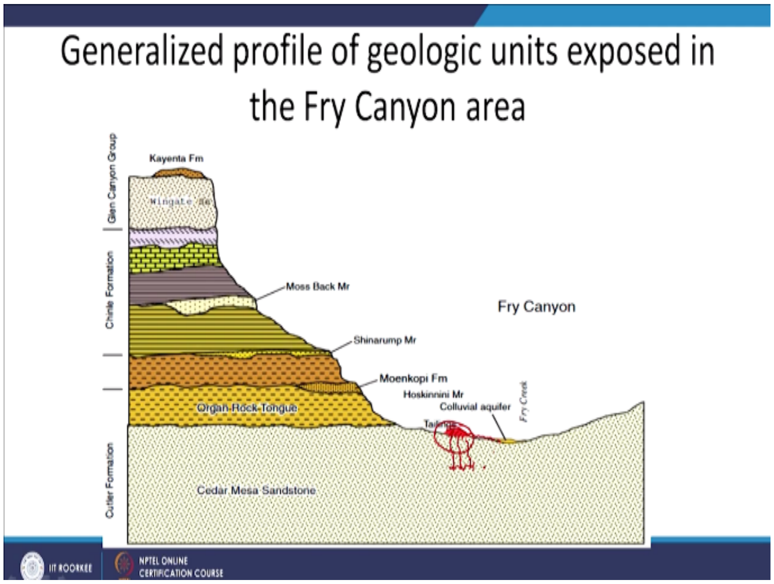

Generalized profile of geologic units exposed in the Fry Canyon area

So moving on I guess we talked about stratigraphy, so later on maybe a couple of sessions later let us say we are going to look at a particular case study and we are going to come back to that. So the particular case study is that you have uranium mine tailings let us say. And I believe they had a uranium mine and the relevant tailings were what we say contaminating the groundwater and sometimes the surface water I believe right.

So here they looked at the different strata and such. And why is that obviously important you need to be able to get you an idea about again hydraulic conductivity of the relevant strata and how the ground water is flowing through that particular media and so on right, just a quick example here. Again what is the case here you have this is the side view obviously and you have this uranium mined tailings, either the runoff let us say or the relevant leachate was contaminating either the surface water or the groundwater.

And the case that we are going to look at later on is how did the people go about choosing there are a relevant reactive media let us say and how what were the relevant results and such. We will look at this in greater detail later on.

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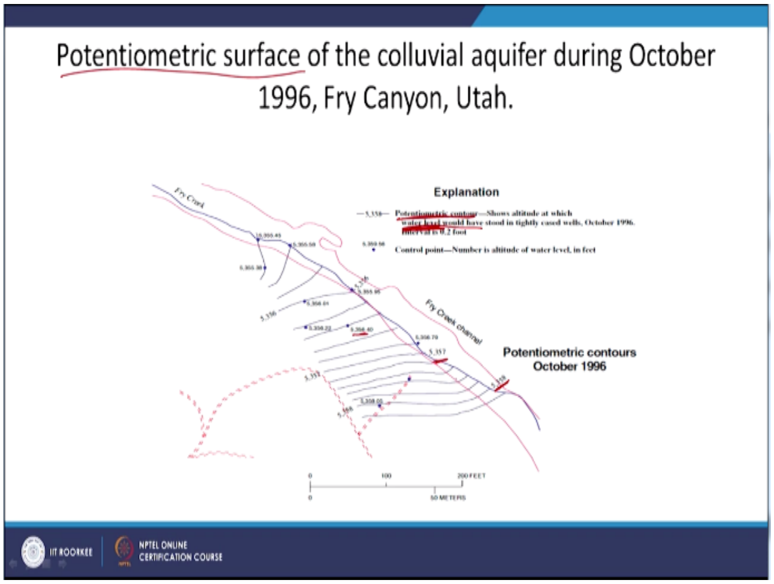

Potentiometric surface of the colluvial aquifer during October 1996, Fry Canyon, Utah.

Explanation

—5,358— Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells, October 1996. Interval is 0.2 foot

Control point—Number is altitude of water level, in feet

Potentiometric contours October 1996

So obviously for that again as I mentioned earlier you need the Potentiometric surface let us say as I need to get an idea about what is it here, water level right that is what I mean when I refer to Potentiometric contours. So you have piece of materials let us say which can help you get this done let us say and so what will this give me an idea about. Let us look at the contours here, so I have 5358 here, 357 here, 356 here and so on right.

So typically let us say I can from this contours estimate the groundwater flow direction, yes; from these contours or the relevant measurements let us say I can get an idea about or try to get you an idea about the groundwater flow direction, yes.

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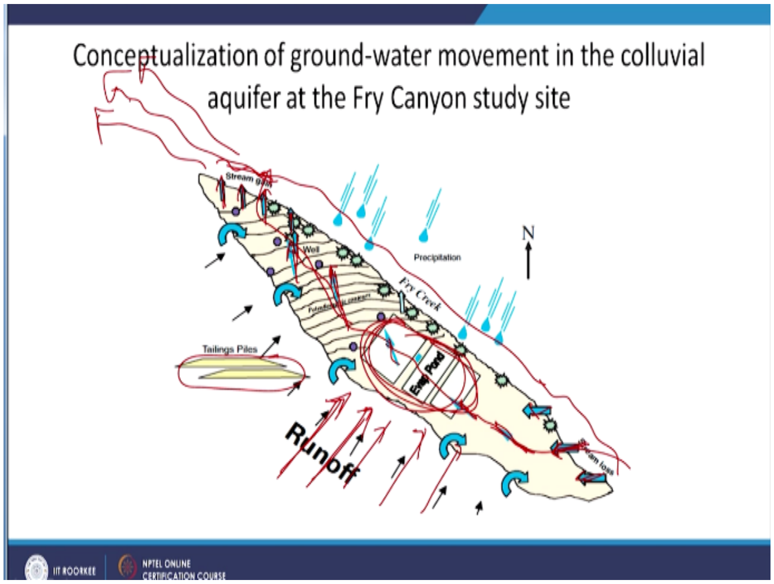

Conceptualization of ground-water movement in the colluvial aquifer at the Fry Canyon study site

So moving on, so this is what we see here. So once people develop that particular contour model let us say right or estimated the contours of the potentiometric surface what did we get? So we see that let us say depending upon whether we have rainfall or not in this case we do have rainfall; we have runoff directly you know coming in contact with these particular contaminated zones yes, that is one case obviously right and you have the tailing piles.

Here I guess evaporation pond that was under case, yes. So you have these particular cases, yes. And here you have the groundwater flow and I believe this was the groundwater flow, yes. So the case is that you have the stream here if I am not wrong you have a stream flowing around here. So initially let us say the water from the stream flowed into the site let us say or you know the aquifer for groundwater aquifer was recharged by the surface water what we say source let us see, and that is what you see here and then the groundwater flow in this direction.

And later in regarding because of the contours let us say again from the particular aquifer or groundwater again join the stream here right. So what does this mean, now right. So water from the stream let us say can recharge the groundwater, get contaminated here right the zone contaminated here and then what can happen it can contaminate to wider area and as it flows through and again reaches the stream though, right.

And now the stream can take the water or the containment water how would at greater extent, right. So the case here was that initially let us say the water; the contours were such that the water from the stream let us say was recharging the groundwater upstream of the relevant contaminated site, right.

And then the groundwater let us say was being contaminated at the relevant contaminated sites right and then flowing through during this process obviously you are going to have the soil contamination obviously groundwater contamination and then the key aspect was this particular groundwater containment groundwater was again joining or rejoining the stream right. In such a case what would you expect?

Again, here that it is the case of transport of the relevant containment with in this case uranium or a remarkably wider extent of area and thus greater number of people being affected by the relevant contamination, right. So again the key is that the aspect that I am trying to convey is that you know you need to be able to understand how water moves; why is that because obviously that is typically is how let us say or the factor which decides let us say the contaminant transport, right. So that is one aspect.

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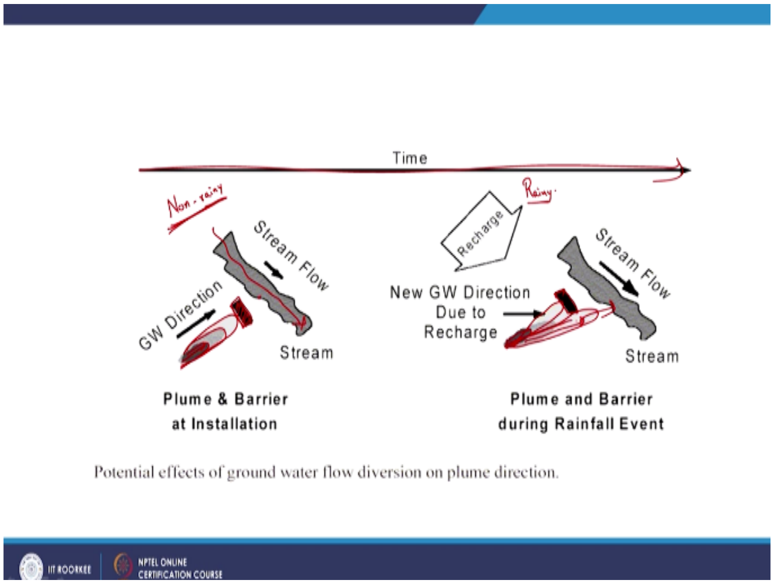

Potential effects of ground water flow diversion on plume direction.

And then the other aspect obviously that we need to look at is if when we were discussing the relevant previous slide I mentioned that this was during rainfall or during precipitation let us see. The key is that you need to be able to understand the relevant flow paths let us say groundwater flow paths and such, both during the rainy season and non-rainy season. Why is that? We are going to look at the particular case here.

So here let us say this was during the non- rainy season and people estimated the groundwater plume to be in this direction and based on that they estimated the location of the PRB designed the PRB and put that in right and why is that, they have a river or stream here and they did not want the contaminant to reach this particular stream here right. So but the case was they only based their analysis on a non-rainy season let us see.

But as we see here with time or during the rainy season during the rainy season what would you see you would see let us say there is a recharge let us here right. And now the groundwater flow due to recharge is now more in this direction but as you can see it has shifted, right. So it has shifted towards this direction, thus it does not flow through the PRB and now some contaminating the relevant stream, right.

So when you take into account the relevant what do we say measurements are such or you need to get when you're trying to get you an idea about the contaminant plume or the groundwater flow direction and such it is critical that you measure it throughout the year preferably during let us say two years let us see if not two years I guess that is what we say that would be erroneous to say.

So as in to look at draught non-draught seasons too, right and also certainly rainy and non-rainy seasons, right. So that is one particular aspect. And as I mentioned earlier when people think that PRB failed but it is not the failure of the PRB but inaccurate estimation of the direction of the plume, right. So that is one aspect we need to consider.

So let us say at this stage what do I know? I knew now or you know have an idea about the concentration of the contaminants, type of contaminants, the plume size and distribution, aquifer characteristics, groundwater flow characteristics and so on and so forth, right. So now what next, right. And now based on this I need to now let us say take a decision whether I can put in more resources and go for further testing or such.

So let us say I have been able to take the decision as in let us say I demon that based on literature or available site conditions that PRB installation is a worthwhile way to going about it, okay. I am willing to spend resources. What next now? So obviously, I need to come or you know choose the relevant reactive media, right. How do I choose the relevant reactive media? Am I going to put him what we say number of what do we say PRBs in the groundwater and then test it again that is a costly exercise.

So what am I going to do I am going to choose what do we say from literature or from experience many different kinds of or reactive media, right. I mean reactive media that would make sense in that particular context of the contaminant right. And then I am going to conduct tests in the lab either the batch tests or the column tests, right.

And from those batch tests and column tests I will see let us say first from the batch test I will see batch tests right closed system I will see let us say once the system has reached equilibrium let us say or if and when the system has reached equilibrium those conditions do they meet my relevant criteria, okay. If they do so then the column test as in with respect to timeline I need to look at the kinetics to let us say right.

And the adsorption desorption or reduction and such, so column tests and such, right. Or to also understand when the breakthrough occurs typically, right but typically breakthrough you would not want that to happen. Obviously you are going to have a lot of reactive media such that breakthrough does not happen breakthrough let us say layman's terms is that, if I have PRB here and how concentration.

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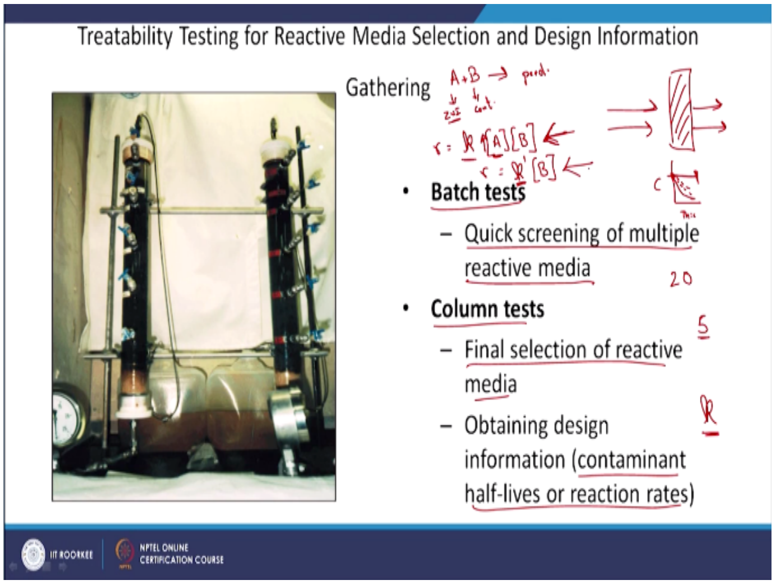

Treatability Testing for Reactive Media Selection and Design Information Gathering

- **Batch tests**
  - Quick screening of multiple reactive media
- **Column tests**
  - Final selection of reactive media
  - Obtaining design information (contaminant half-lives or reaction rates)

We just looked at the term breakthrough let us just try to understand that in the context of PRB, so groundwater is coming in this direction let us say, right and is living in here right. So typically let us say the concentration that profile that you would want is this, this is the concentration and thickness of the PRB, right.

But typically over the time you will have exhaustion of your relevant reactive media they will be exhausted let us say, right and then you are going to end up with profiles like this and you would have a breakthrough here right as in the concentration at the inlet is the same as the concentration as the outlet now. But obviously we will design the PRB in such a way that we avoid that. But again these are aspects that you check.

So what do we look at? We look at batch test to see that let us say multiple reactive media to see at the equilibrium conditions are the relevant is their removal or not and if there is removal is there sufficient removal or not. Then obviously, column tests let us say on some of the screened criteria let us see here I end up with 20 and now after screening I have 5 and then these will help me come up with final screening of the reactive media.

And obviously to understand let us say the retention times are such or containment half-lives, estimate the rate constants and such, right. For example, let us say for some reactive media you will have the rate constant, right. But for some let us say you might not or you might not have the pseudo first order rate constants or such so how do I get that, I will get them from the column test, yes. Again when I am talking about rates but I assume most people have some chemical process based background but for those people who do not have the background let me just list that out here or you know try to explain that here.

Let us say if A+B reacting to form some products let say, in this case let us say this is zerovalent iron and this is my relevant contaminant, right. What is the rate of my reaction, it is going to be equal to r=k times K is the rate constant, right depends on temperature certainly; time concentration of A, times concentration of B, right.

So typically concentration of A or the zerovalent iron is so high that you can assume that it is a constant. So what will this transform into it will transform into K dash times concentration of B, so that is my rate. And what is this K dash, that is my pseudo first order rate constant as in as you see here it looks like it is a second order or it is supposed to be second order but it seems like a first order so that is why we call that particular reaction to be a pseudo first order reaction, right.

So again based on my column tests let us say I will be able to estimate the relevant rate constants so that will give me an idea about which particular what we say reactive media what do we say brings about the relevant removal relatively fast, right. So those aspects are going to be looked at and based on these tests I will be able to choose my final reactive media but I am going to place in the ground water in my PRB, right not in the groundwater pardon me in the PRB.

So I guess I am running out of time so I will end my particular session for now and we will move on to the relevant aspects with respect to let us say monitoring and more importantly design in the next session and then we will move onto looking at the case study in greater detail, right. So; and with that I take leave and thank you.