Identifying Soil Erosion Risk for Onshore Pipelines:

Advanced Engineering Geographical Information Systems for Pipeline Design

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Abstract The effects of soil loss worldwide are a major concern; it impacts on the environment, food security and public health. Within the global context, soil erosion has a significant impact on the environment; causing damage through sedimentation, pollution and increased risk of flooding. In addition, eroded soils may lose 75 per cent of their carbon content, leading to increases of carbon emissions to the atmosphere. Although soil loss is a natural process it is greatly increased by anthropogenic activity impacting on land management practices, such as farming and construction.

For pipelines however, the major concern is to minimise the impacts of individual storms before the bio-restoration has become effective, therefore consideration must be given to the potential level of damage of a design storm. Failure to manage this can lead to the exposure of the buried pipeline causing the pipeline to free span, which can lead to catastrophic failure due to cyclic loading or vortex induced vibrations.

The method presented yields results which offer significant correlation to the field observed data. This method should be seen as best practice for preliminary soil erosion risk assessment for onshore pipelines to form the basis of the subsequent field verification.

Keywords Soil Erosion • GIS • Pipeline Routing • USLE

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Preface

This paper is based on research carried out as part of a PhD thesis titled: *'Advanced Engineering Geographical Information Systems for Pipelines'*, due for submission in 2015.

The presentation slides are attached at the end of this paper.

Glossary

ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
SRTM	Shuttle Radar Topography Mission
USLE	Universal Soil Loss Equation

1. Introduction

This paper proposes a method for using GIS and public domain remote sensed data to perform a preliminary soil erosion risk assessment for onshore pipelines. The benefits of undertaking this preliminary assessment are:

- Early identification of the potential soil erosion risk, enabling it to influence the route selection process.
- Provide data to target the subsequent field investigations, reducing costs and time required.
- Help to minimise the environmental impact of the pipeline, leading to sustainable, responsible engineering.

While many of the environmental challenges on a pipeline project can be mitigated to some extent through proper route selection, soil erosion is largely a product of the installation method of the pipeline and therefore can only be minimised through the use of the correct erosion control methods (Morgan et al., 1984).

In order to determine the erosion control measures required and therefore the erosion control cost associated with a particular route, an erosion control classification survey is carried out.

2. Soil Erosion

> *"Soil erosion is the wearing away of the land surface by physical forces such as rainfall, flowing water, wind, ice, temperature change, gravity or other natural or anthropogenic agents that abrade, detach and remove soil or geological material from one point on the earth's surface to be deposited elsewhere."*
>
> *(Bowyer et al., 2009: 2)*

Erosion due to water is broadly defined as being:

- Sheet or inter-rill: where the soil is removed in uniformly thin layers and the flow is unconfined (overland flow).
- Rill: initiated at a critical distance down slope when the overland flow becomes channelled. This is temporary and can be ploughed out.
- Gully: confined, channelled and permanent.

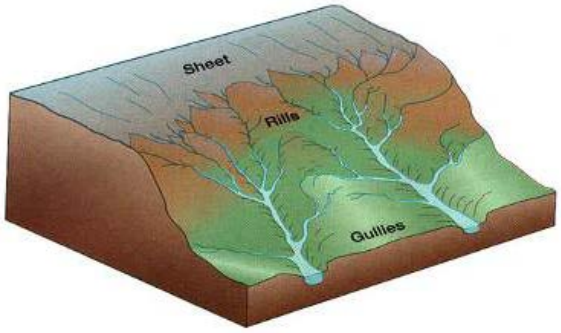

Figure 1 – Erosion types (Sheet, rill and gully)

The severity of the erosion is rated by a simple scoring system based on the identification of the visible erosion features (Table 1), with the accepted sustainable rate of soil loss being less than 10 tons ha^{-1} $year^{-1}$ (erosion risk 3) (Morgan, 2005).

Erosion Risk	Erosion Rate (tonnes/ha)	Visual Assessment
1	< 2	No wash marks or scours.
2	2 – 5	Shallow rills every 50 – 100m.
3	5 – 10	Discontinuous rills every 20 – 50m.
4	10 – 50	Continuous network of rills every 5 – 10m or gullies every 50 – 100m.
5	50 – 100	Continuous network of rills every 2 – 5m or gullies every 20m.
6	100 – 500	Continuous network of channels with gullies every 5 - 10m.
7	> 500	Extensive network of large gullies every 20m

Table 1 – Erosion Risk Classification (Morgan, 2005)

The effects of soil loss worldwide are a major concern; it impacts on the environment, food security and public health (Bandara et al., 2001; Pimentel, 2006). It is estimated that 75 billion metric tons of soil worldwide are lost per annum, with Africa, Asia and South America typically experiencing average losses of 30 to 40 tons per hectare per annum (t ha^{-1} $year^{-1}$) (Pimentel et al., 1995).

> *"On the basis of its temporal and spatial ubiquity, erosion qualifies as a major, quite possibly the major, environmental problem worldwide."*
>
> *(Toy et al., 2002: 2)*

Apart from the societal costs, soil degradation and loss due to erosion has significant economic impact; the cost to the US economy is estimated to be between US$30 billion (Uri & Lewis, 1998) and US$44 billion (Pimentel et al., 1995) annually, while the annual cost in the UK is estimated at £106 million (Pretty et al., 2000). In Indonesia the cost is estimated at US$400 million per year in Java alone (Magrath & Arens, 1989).

These costs result from the combined impact of both on-site and off-site effects due to soil erosion.

2.1 On Site Effects

On-site impacts include the loss of soil function from the breakdown of the soil structure and the reduction in organic matter. The outcome of this is reduced yields, loss of arable land, reduced food security (Cohen et al., 2006; de Vente et al., 2008; Römkens et al., 2002) and risk to existing infrastructure such as roads, railways and pipelines (Qi et al., 2012).

2.2 Off Site Effects

Off-site effects due to the transportation of sediment include the increased turbidity in water courses leading to public health issues and a risk to hydrological infrastructures, such as hydroelectric generation and irrigation schemes, primarily due to increased wear on bearings and abrasion damage to impellers and pumps (Holmes, 1988).

Figure 2 – Caspian Sea showing eutrophication http://visibleearth.nasa.gov/view.php?id=66761)

With increased turbidity comes the potential for eutrophication or hypertrophication, which is the response of aquatic systems to raised levels of nitrates or phosphates. This leads to hypoxia, a reduction of oxygen in the water and rapid growth in algae (Ekholm & Lehtoranta, 2011; Vollenweider, 1970). An example of this is the Caspian Sea (Figure 2), where eutrophication of the northern part of the sea is due to soil erosion washing nitrates and phosphates into the Volga and Ural rivers. (Leroy et al., 2007).

3. Modelling Soil Erosion

The effective use of erosion control modelling in agriculture has long been established, with early work carried out in America by Hugh Bennett in the 1920s. From this work, mathematical models to predict soil loss have been developed, the Universal Soil Loss Equation (USLE) (Equation 1), issued in 1965 (Wischmeier and Smith, 1965) and the Revised Universal Soil Loss Equation in 1978 (Wischmeier and Smith, 1978); further models have since been developed, including the Morgan-Morgan-Finney (Morgan, 2001, Morgan and Duzant, 2008) and the European Soil Erosion Model (Morgan et al., 1998). While all the models generally consider the same fundamental factors of erosion, the later models consider factors such as seasonal variation and sediment transportation which require more data for the model. For this study, the USLE has been adopted, which is given as:

$$A = R \times K \times L \times S \times C \times P \qquad (1)$$

Where
A = Mean annual soil loss (t/ha)
R = Mean Annual Rainfall erosivity factor (MJ.mm/ha.h)
K = Soil erodibility factor (t.ha.h/ha.MJ.mm)
S = Slope steepness factor (dimensionless)
L = Slope length factor (dimensionless)
C = Crop management factor (dimensionless)
P = Erosion control practice factor (dimensionless)

While the USLE is described as universal, its database is restricted to the soils east of the Rocky Mountains, though further research has been conducted so that it can be used in other geographical areas (Dabral et al., 2008, Roose, 1977) and to the application to the construction industry (Gray, 1996, Gray and Leiser, 1982).

The pipeline route in this study is shown on a Landsat™ visible bands image (Slide 7).

4. Methodology

While it has been established that the natural sustainable rate of soil erosion is somewhere in the region of 1.5 t ha^{-1} $year^{-1}$ (Wilkinson & McElroy, 2007), it is very difficult to measure the rate of soil formation due to the slow process. Because of this, another approach is to view areas prior to construction as being in equilibrium and therefore the soil loss tolerance would be the current rate of soil loss; a quantifiable approach which is better suited to construction projects (Montgomery, 2007; Morgan, 2005). In order to quantify the erosion risk, a classification system is used (Morgan, 2005), ranging from Class 1, very slight to Class 7, catastrophic based on the annual soil loss (Table 1). Using the remote sensed data, estimates were calculated for the required inputs to the USLE.

A detailed explanation of the methodology is given in (Winning & Hann, 2014).

4.1 Rainfall (*R*)

The major concern for newly installed pipelines is to minimise the impact of individual storms before the soil erosion control methods have become effective, thus consideration must be given to the potential level of soil loss for individual design storms (Hann and Morgan, 2006). Design storms are defined by three factors:

- rainfall intensity,
- duration, and
- return period.

While the choice of values for the factors is subjective, conservative estimates for rural areas are generally taken as 10 minutes for the duration of rainfall intensity (Morgan, 2005), 1 hour for catchment areas up to 400 ha, flow paths up to 1,000m for the storm duration (Hudson, 1995) and a return period of 10 years (Morgan, 2005).

The kinetic energy of the rainfall in the storm is determined using Equation 2, (Laws & Parsons, 1943):

$$E = 0.119 + 0.0873 log_{10} I \qquad (2)$$

Where

$E =$ Kinetic energy per mm of rain (MJ/ha.mm)

$I =$ Rainfall intensity (mm/h)

In the absence of detailed rainfall data, it has been estimated from the World Meteorological Organization, which provides data through the United Nations Statistics Division of the Department of Economic and Social Affairs. The value obtained for *R* was then modified as the kinetic energy of the rainfall is inversely proportional to the air density raised to the power of 0.9 and the determination of the kinetic energy of the rain is based on studies that have been carried out at low altitudes. Therefore an adjustment to the rainfall erosivity factor *R* is required with an increase of 7% for every 1,000m of elevation (McIsaac, 1990). Using this method, a choropleth map was produced (Slide 8).

4.2 Soil Erodibility (*K*)

The only accurate method of determining the soil erodibility factor is to undertake measurements from field plots over a period of time. However, some work has been carried out using Landsat imagery to determine the Normalised Difference Vegetation Index (NDVI) (Mathieu et al., 1997) which can provide data on bare soils to an accuracy of 85% (Büttner & Csillag, 1989; Verbyla & Richardson, 1996).

Within the ESRI™ online datasets, there are a number of merged Landsat™ datasets, including vegetation analysis, using the Landsat bands 5, 4 and 3, where healthy vegetation is bright green and soils are mauve. In order to extract the RGB values from the image, it was converted to a single band image with a cell size of 40m x 80m; this is due to the restriction of the raster size of 15,000 by 4,100 (columns, rows). This new image (Slide 9) was then classified into 5 classes.

4.3 Slope Steepness (*S*) and Length (*L*)

In order to determine the slope steepness (*S*) and slope length (*L*) factors of the USLE, a digital elevation model (DEM) was used. There are two freely available datasets: the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (SRTM). The ASTER data has an approximate spatial resolution of 30 meters and was first made available in 2009, while the SRTM data has an approximate spatial resolution of 90 meters and was flown in 2000. The ASTER model contains artificial error patterns (stripes and cloud anomalies), which is why NASA consider it to be research-grade only (Hirt et al., 2010).

Given that erosion control classification for pipelines is usually performed to a granularity of 500 to 1,000 meters and the issue with the ASTER dataset, the SRTM was selected for this research. The combined *S* and *L* factors in the USLE equation are expressed as:

$$LS = \left(\frac{x}{22.13}\right)^{n} \times (0.065 + 0.045s + 0.0065s^{s}) \quad (3)$$

Where

$x =$ is the slope length in meters

$s =$ is the slope gradient as a percentage

$n =$ is the exponent for slope steepness

The exponent for slope steepness is determined by the slope grade and is given in (Table 2).

Slope Gradient (%)	Exponent
≥ 5	0.5
< 5 > 3	0.4
≤ 3 ≥ 1	0.3
< 1	0.2

Table 2 – Exponent for slope steepness for the USLE equation (Morgan, 2005)

Using this data, the slope angle was derived using the ArcGIS tool in the 3D Analyst module (Slide 10).

4.4 Crop Management (*C*)

This is the ratio of soil loss for a unit area at a specific site to that from tilled bare soil for the same soil, slope and rainfall conditions. This in effect is the impact that the vegetation has on reducing the soil loss and is different for varying vegetation. Bare soil has a *C* value of 1 and would therefore appear to be the best value to use for newly reinstated areas of construction. However, where care is not taken in the reinstatement and over compaction occurs it is possible for the *C* value to be as high as 1.3 to 1.4, therefore a more conservative value of 1.2 has been selected.

4.5 Erosion Control Practice (*P*)

This is the ratio of soil loss with a given erosion control method compared to soil under the same conditions without any erosion control measures. Where no conservation/land management measures are used, the value is 1.

5. Summary of Results

All the imagery was resampled to the same resolution as the largest spatial resolution dataset (SRTM data at 90m). Using the inputs for the USLE equation described, the estimated soil erosion rate and risk classification were determined along the pipeline route at a spatial resolution of 90m points). This data was then aggregated to 1,000m sections, which is typically the level of spatial resolution used for this type of survey on long distance pipelines. The values obtained using this method, were compared to the erosion risk classification values determined as a result of field observations.

The results obtained using this method corresponded well with the soil erosion risk assessment carried out in the field, with over 69% in agreement and 95% of the results obtained being within ±1 erosion classification identified by the field data (Slides 11 & 12).

6. Conclusion

The results obtained across terrain with very different soil types and slopes for a length of 450km are certainly of an order for the level of results obtained, achieving over 95%, while these results are good it is important to remember that they have only been verified for the climatic and soil conditions of Azerbaijan. While this analysis fits very well with the study area, it would clearly have to be re-validated for areas of significantly different climatic or soil conditions.

The method allows the potential areas, with the exception of major rivers and areas of seismic activity to be identified prior to verification by field investigation. By adding all known major river crossings and areas of seismic activity to the areas identified through the method presented, a targeted approach to the subsequent field verification can be planned. While the approach offers a good insight to the potential soil erosion risk, it has been established through sensitivity analysis, that the method can fail to identify risks associated with very poor soils in relatively flat areas. Therefore, it is recommended that for flat areas in known arid and semi-arid areas, additional soils data is obtained, either through the use of soils maps, Non-Governmental Organisations, or site visits to mitigate this risk. In the absence of additional data being available, then these areas must be identified as requiring field verification.

Similarly, in areas where the slope angle is in excess of 10 degrees, care must be taken so that the erosion risk is not over estimated where the soils are good. Therefore, where these slopes exist in temperate climates, these areas need to be mitigated in the same way as poor soils in flat, arid terrain. As long as the limitations of conducting this type of analysis is understood it is believed that this type of high level screening can be seen as a useful tool for the early identification of soil erosion risk, enabling the engineer to quickly identify the potential areas along the pipeline route that are at a higher risk of soil loss, or are likely to be more challenging in achieving successful bio-restoration. In addition to providing an early indication of the soil erosion risk it will enable the field verification to be more targeted, essential for long distance pipelines.

While this type of analysis can clearly be automated through code or the ArcGIS Model Builder, because of the limitations discussed it is not recommended. It is vital that the analyst has a clear understanding of the uncertainties within the model and is able, through experience and the application of sound engineering methods to correctly interpret the results obtained. By developing a 'black box' solution there is a risk that the results will not be correctly interpreted.
Notwithstanding these issues, by performing this high level analysis will help to reduce the environmental impact of major construction activities and therefore should be seen as best practice.

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He has Masters in both Mechanical Engineering and Geographical Information Science and over 25 years' experience in the field of pipeline design. He is currently reading for a PhD in the development of Advanced Engineering Geographical Information Systems for pipeline design, based on the PODS™ schema.

He is the Lead Pipeline Engineer on a major pipeline project, where he is involved in the development of a PODS™ based model for the design and construction of a pipeline in Azerbaijan and Georgia, which draws heavily on his current research.

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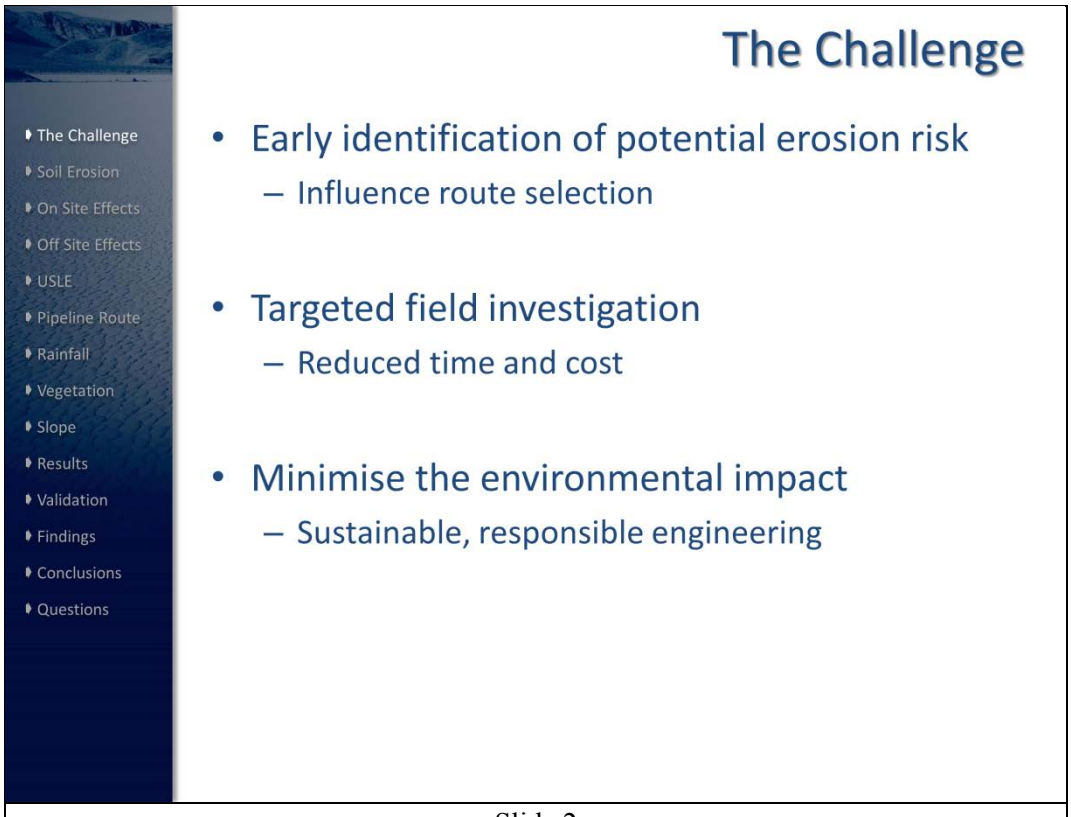
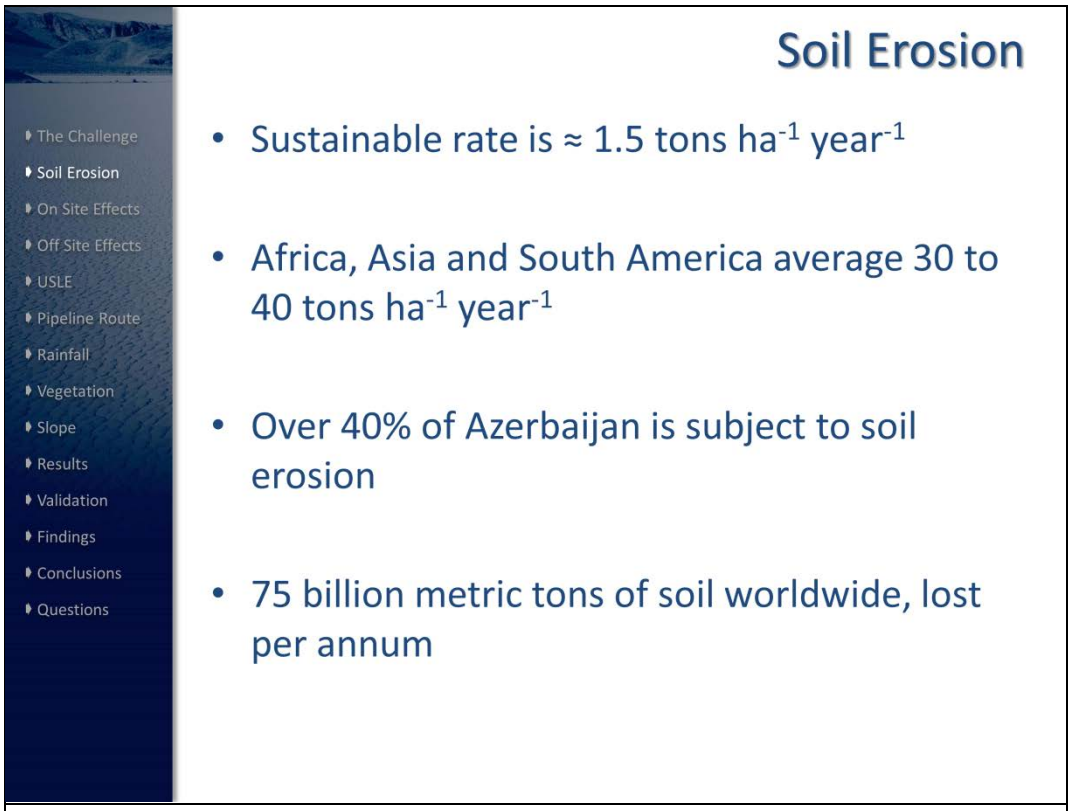
Appendix – Presentation Slides

Slide 1



Slide 2



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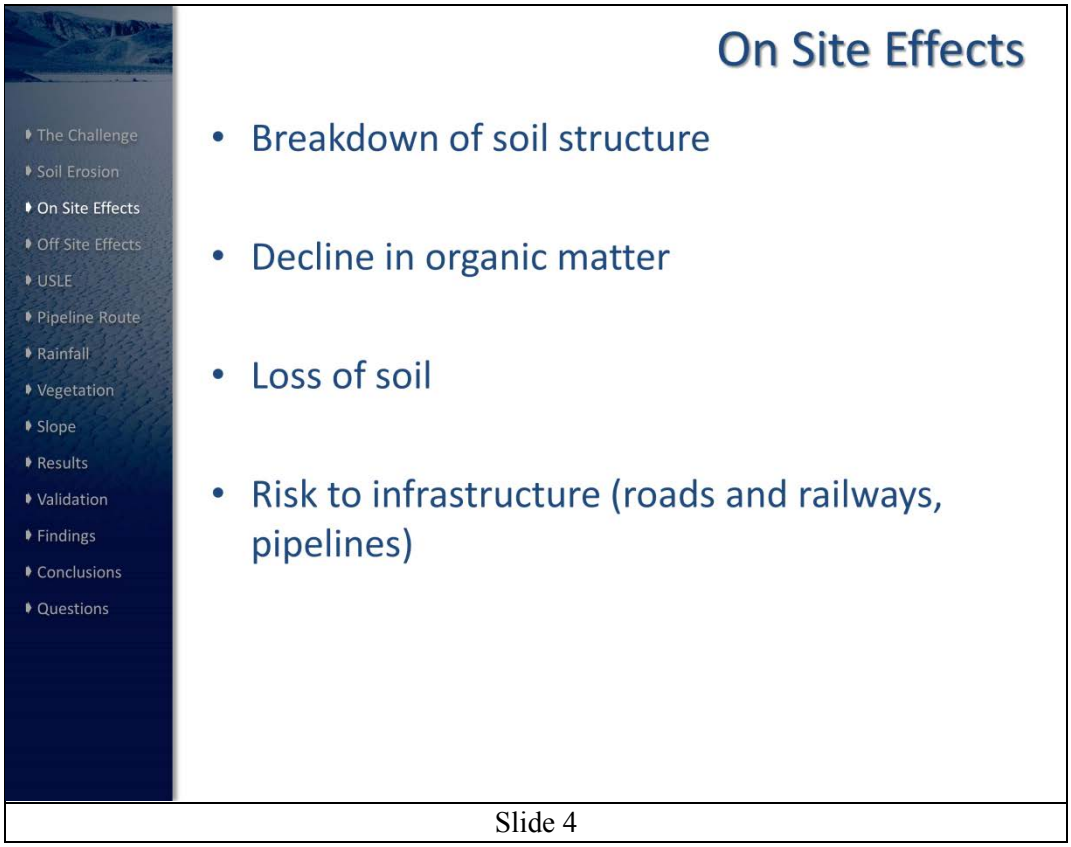

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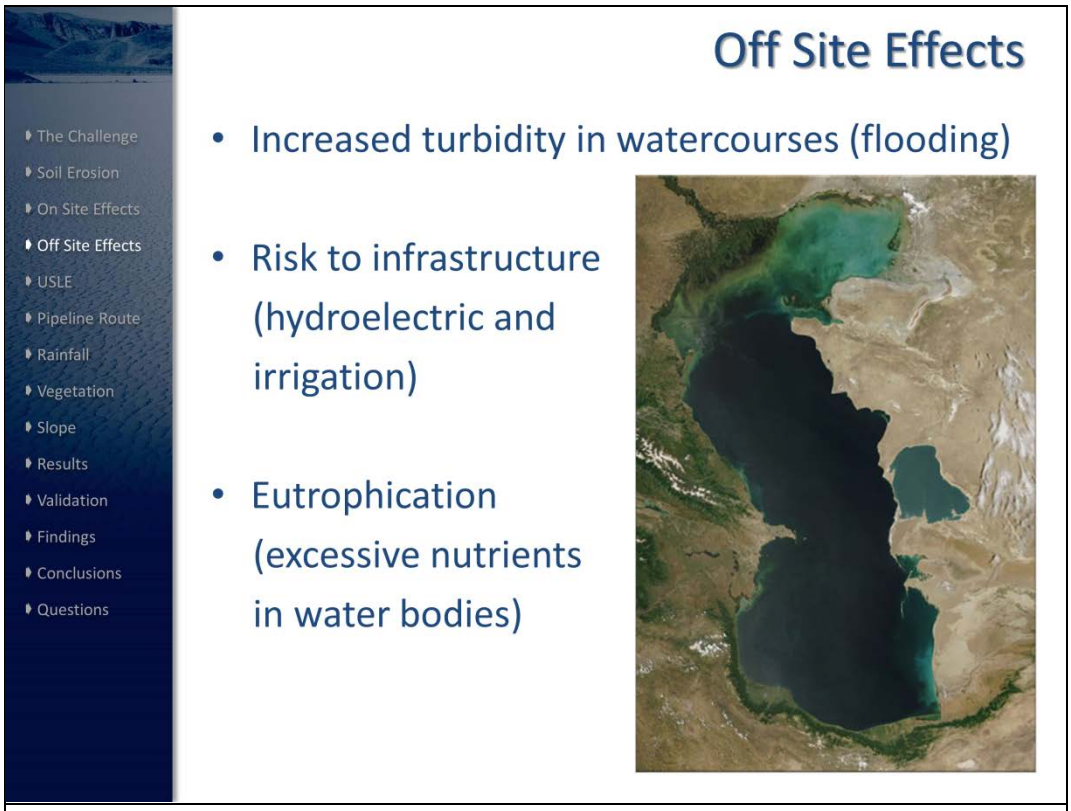

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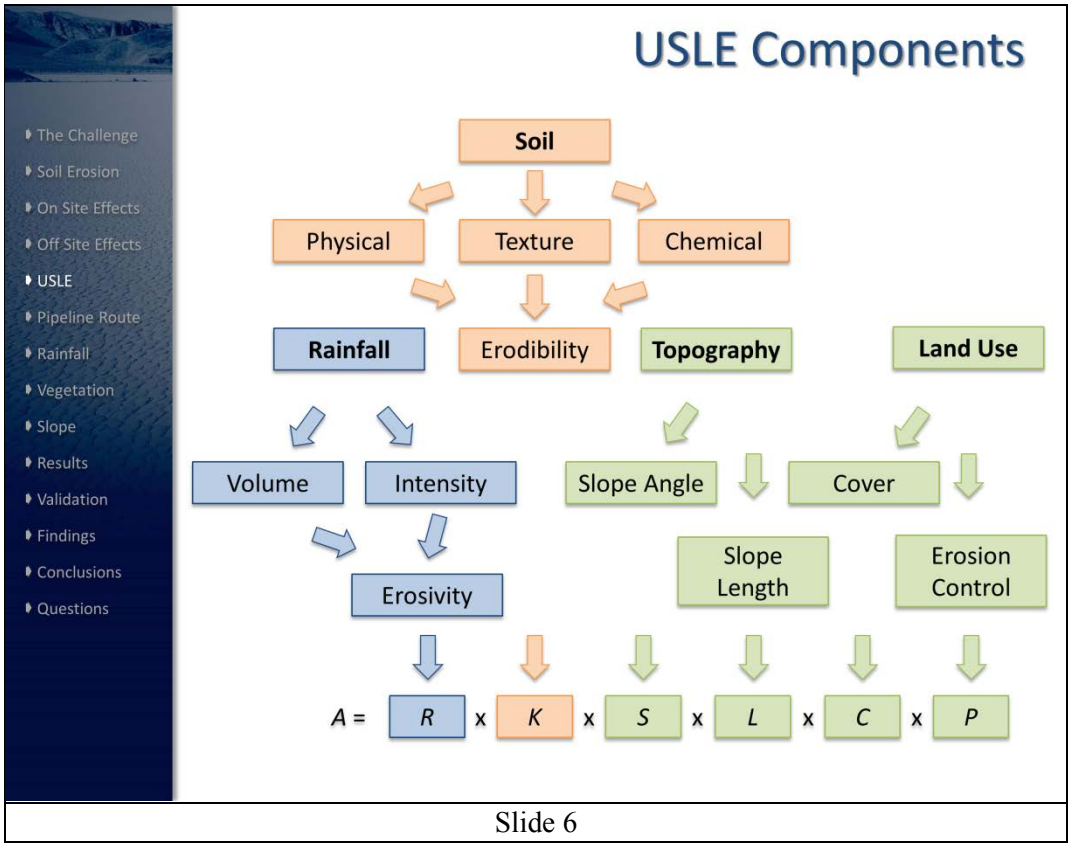

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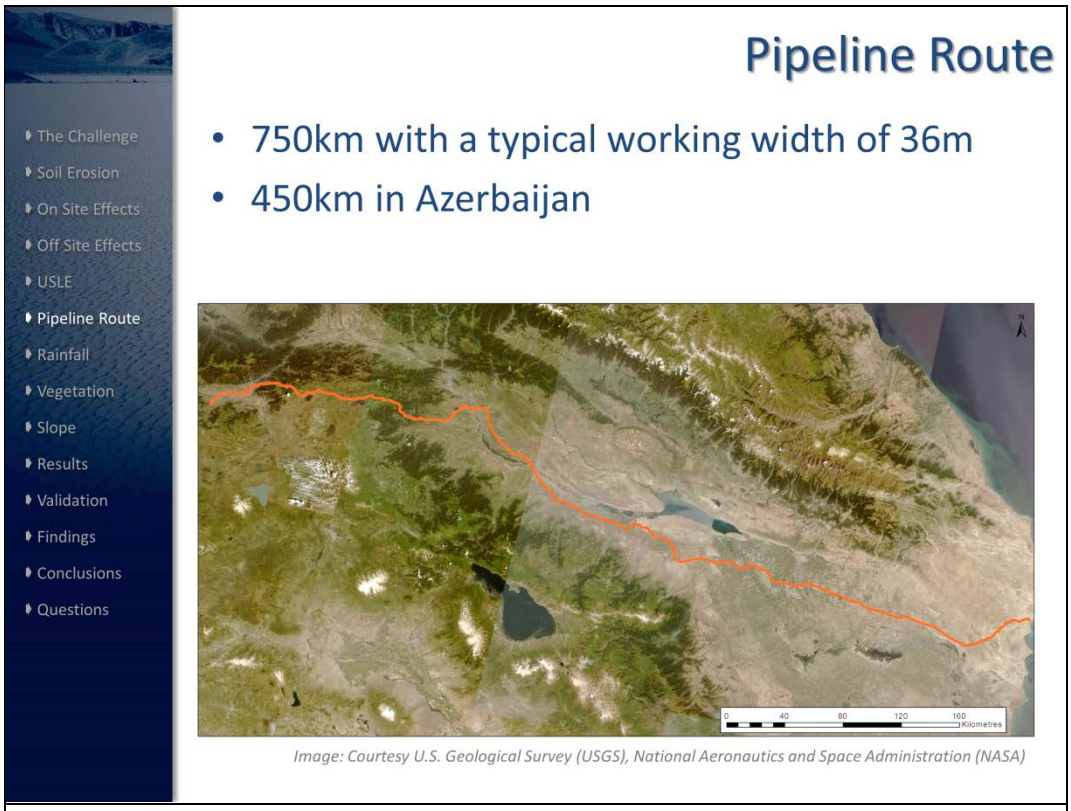

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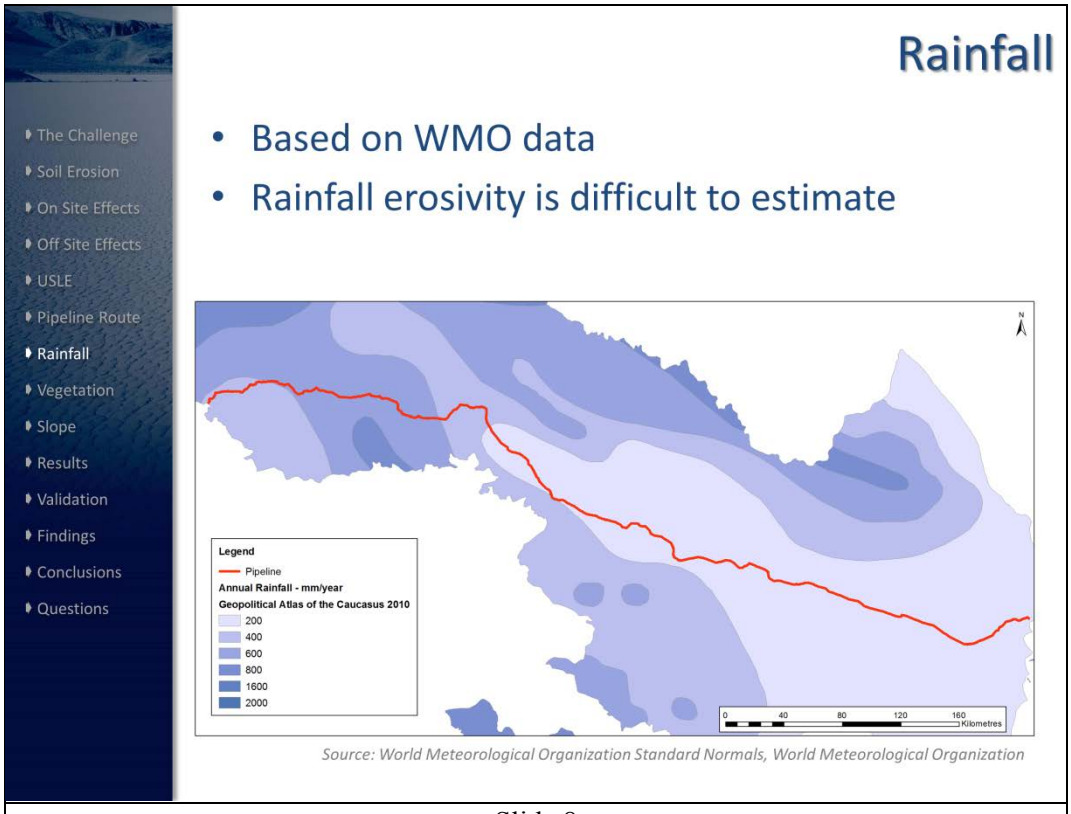

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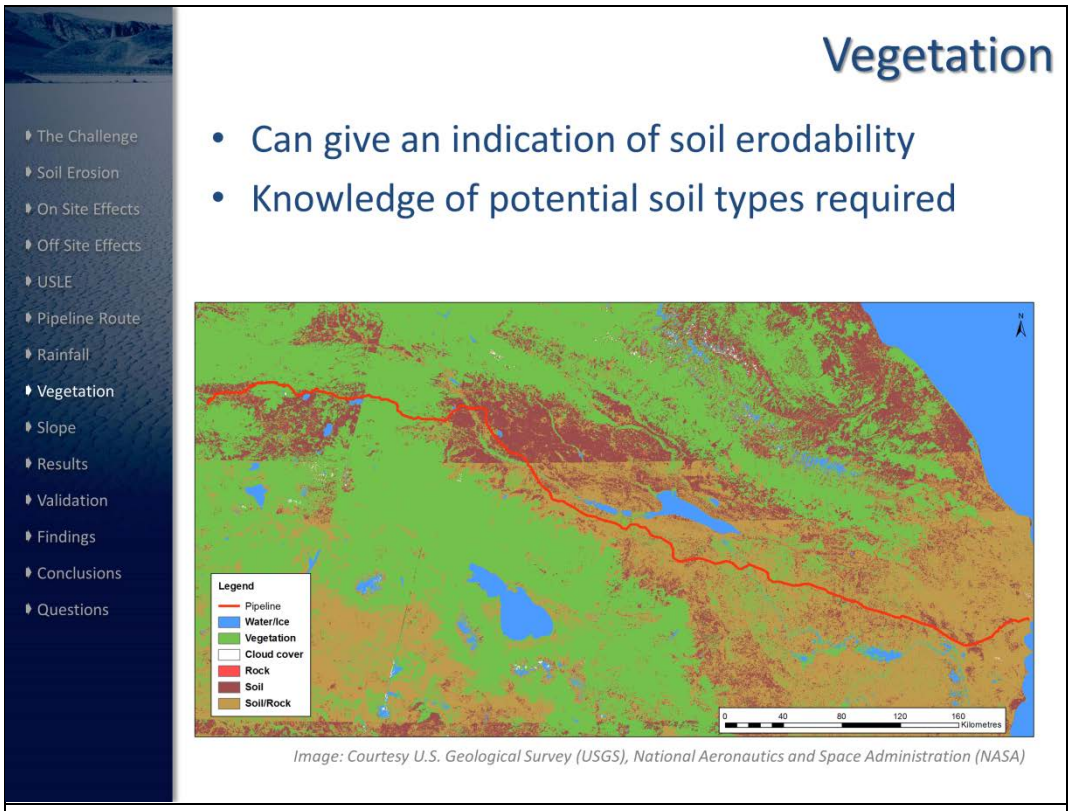

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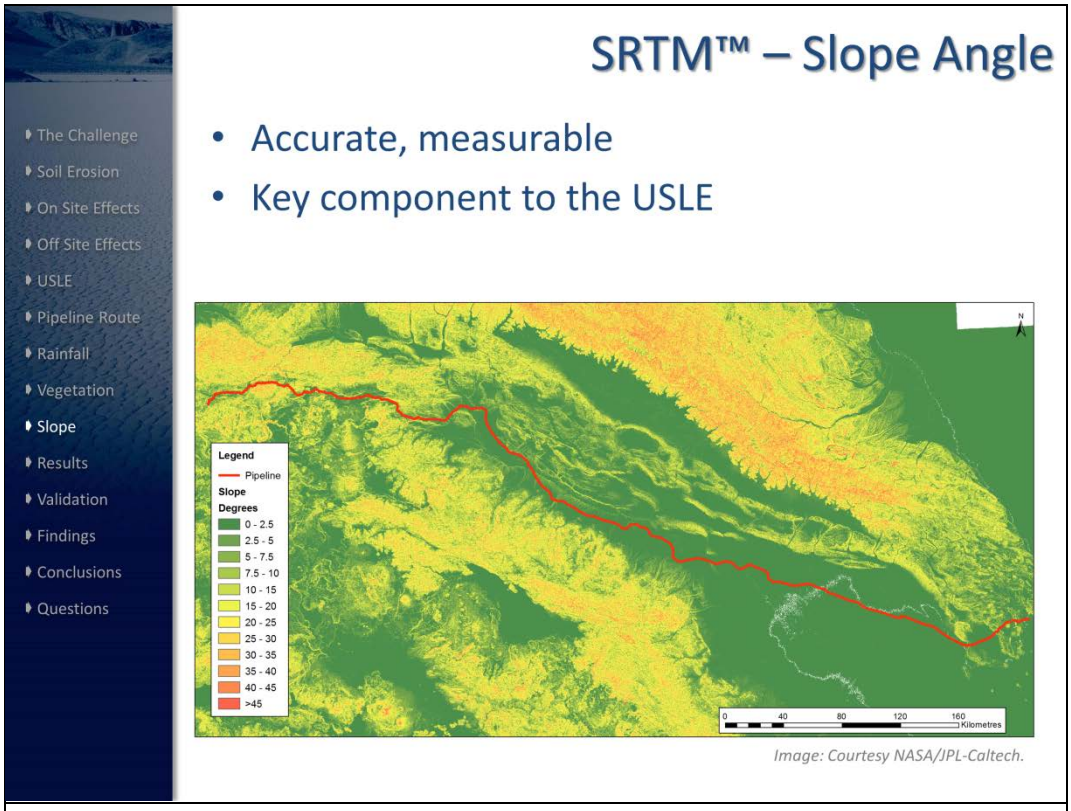

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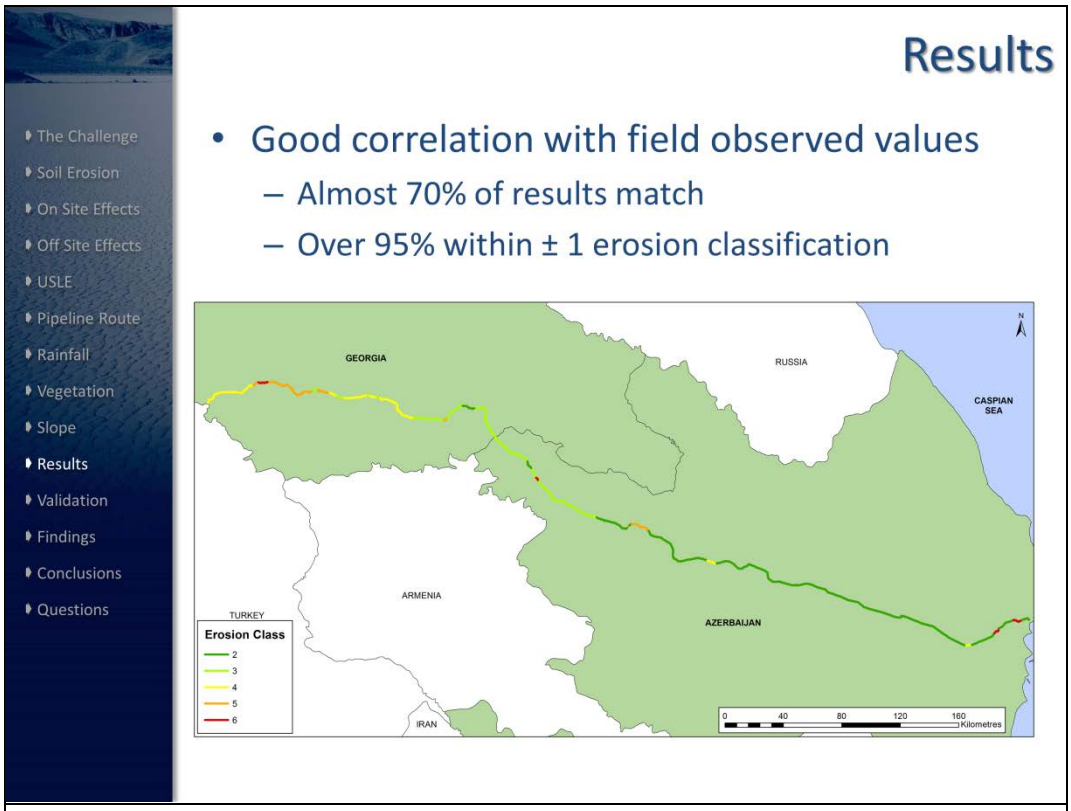
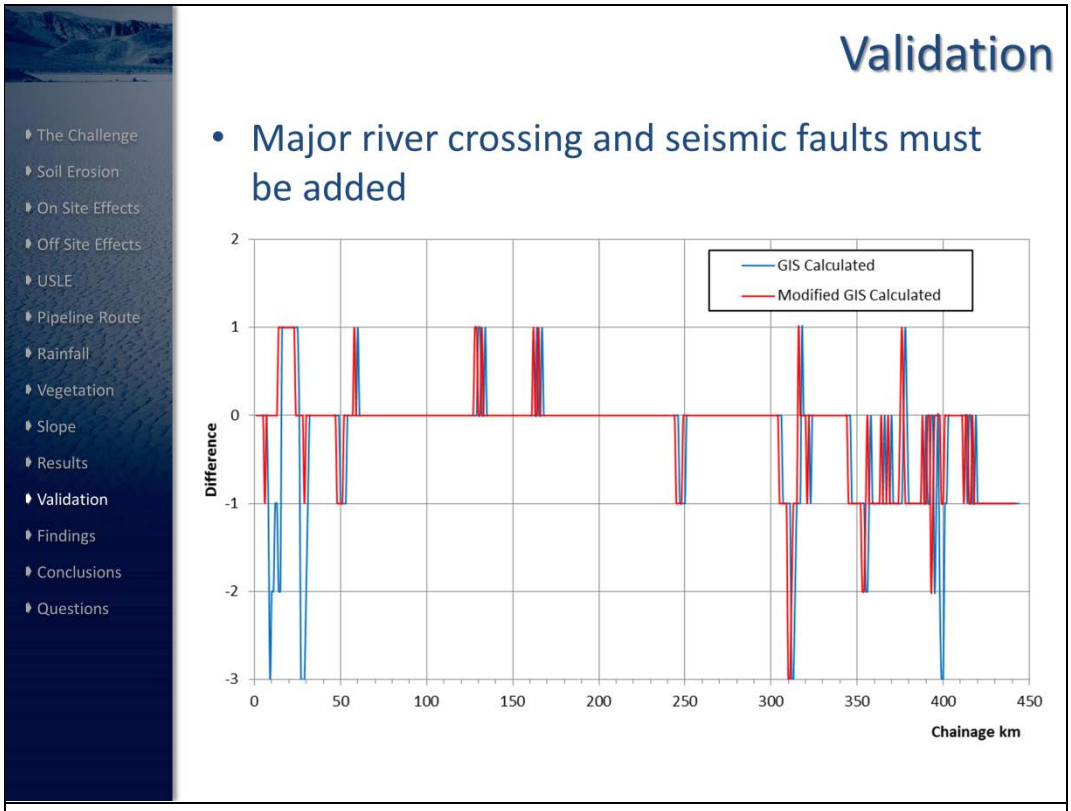
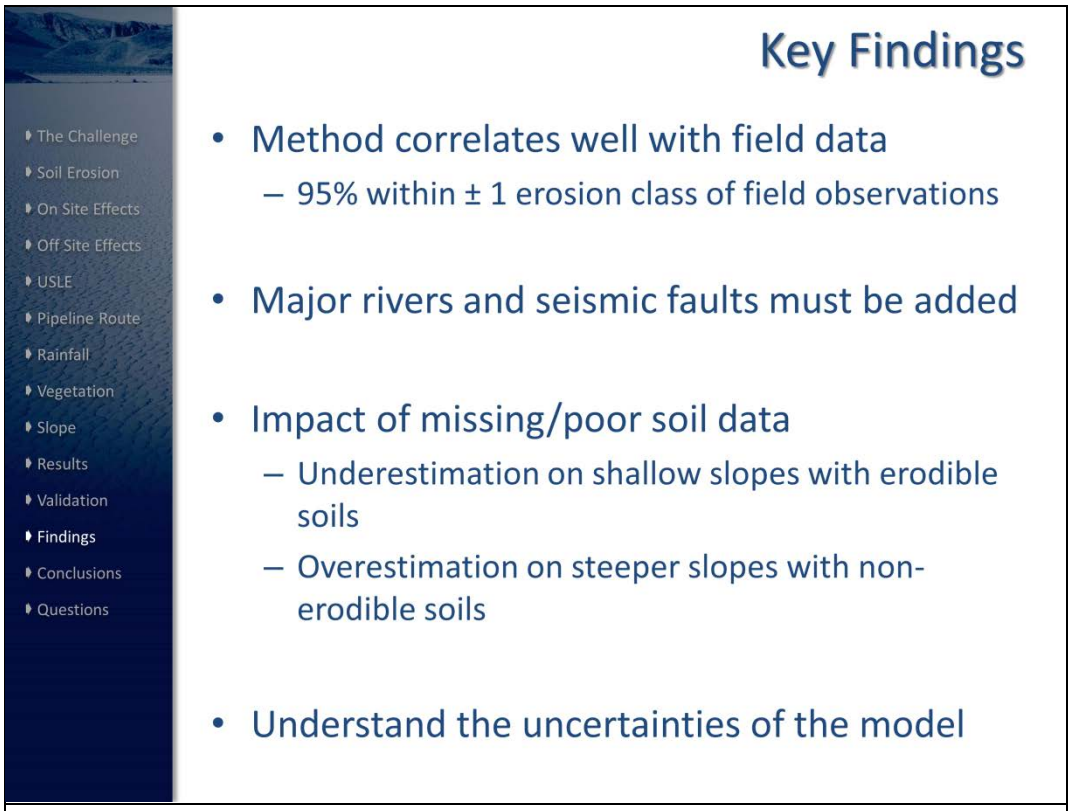


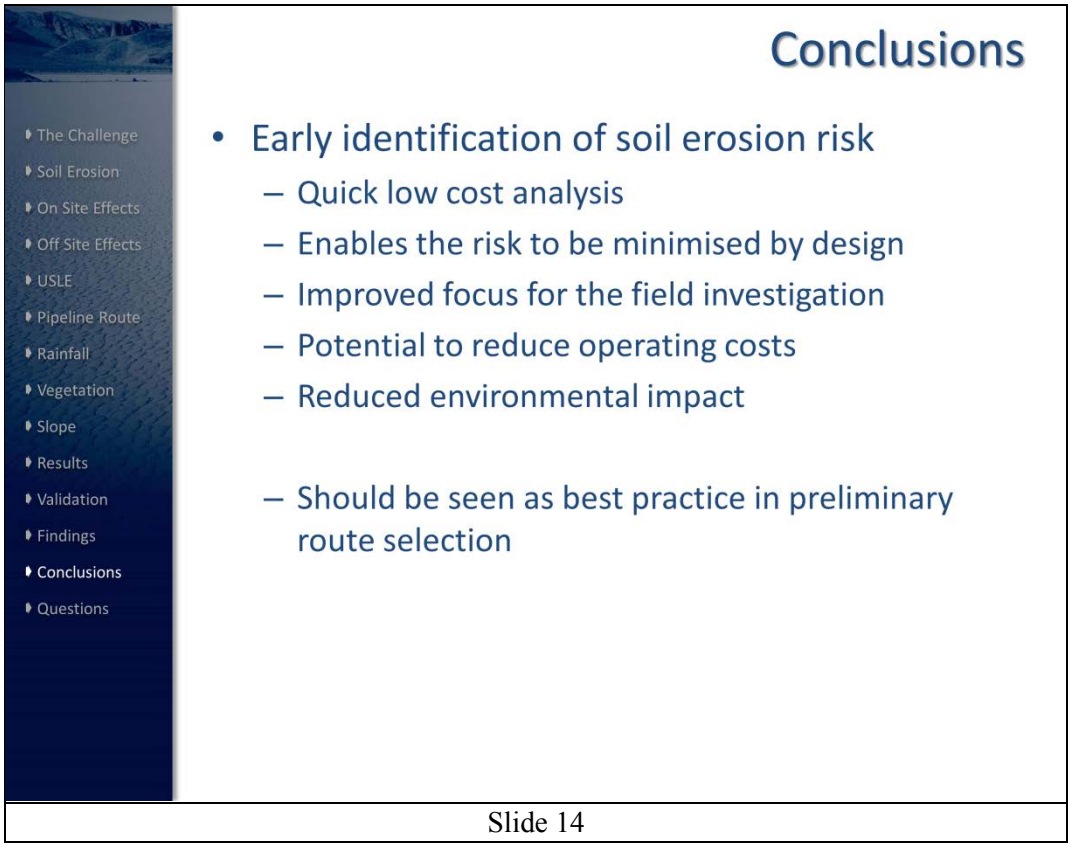
Slide 11



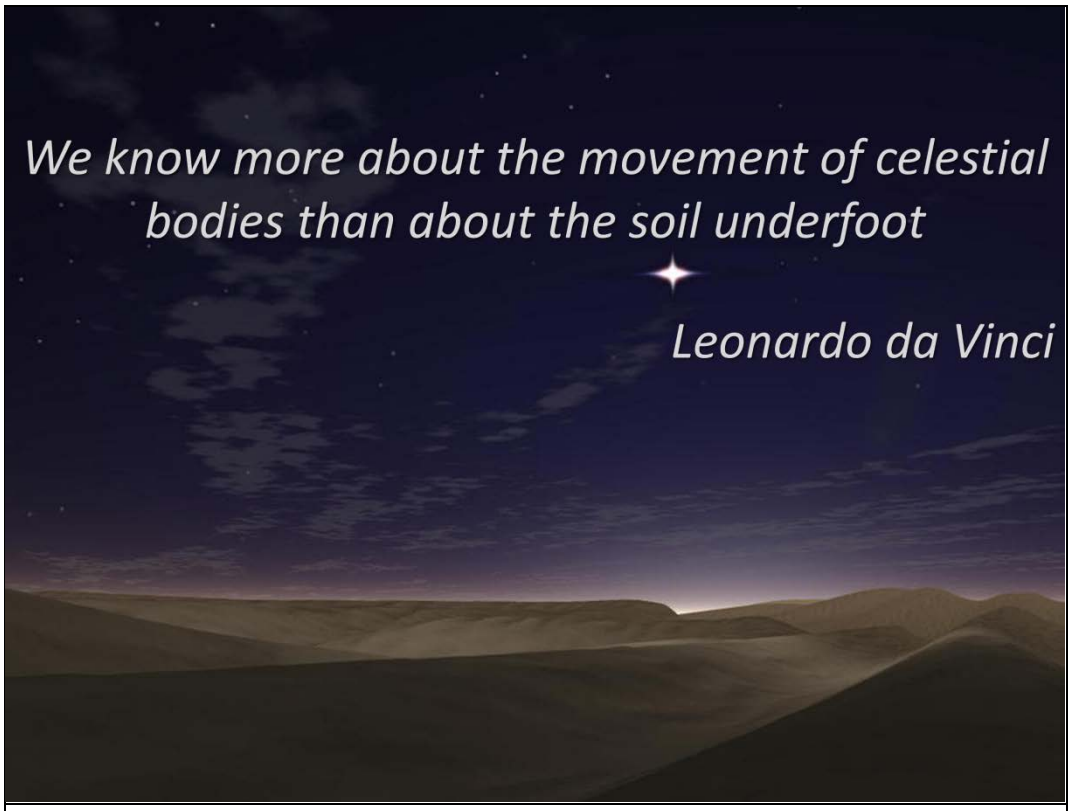
Slide 12



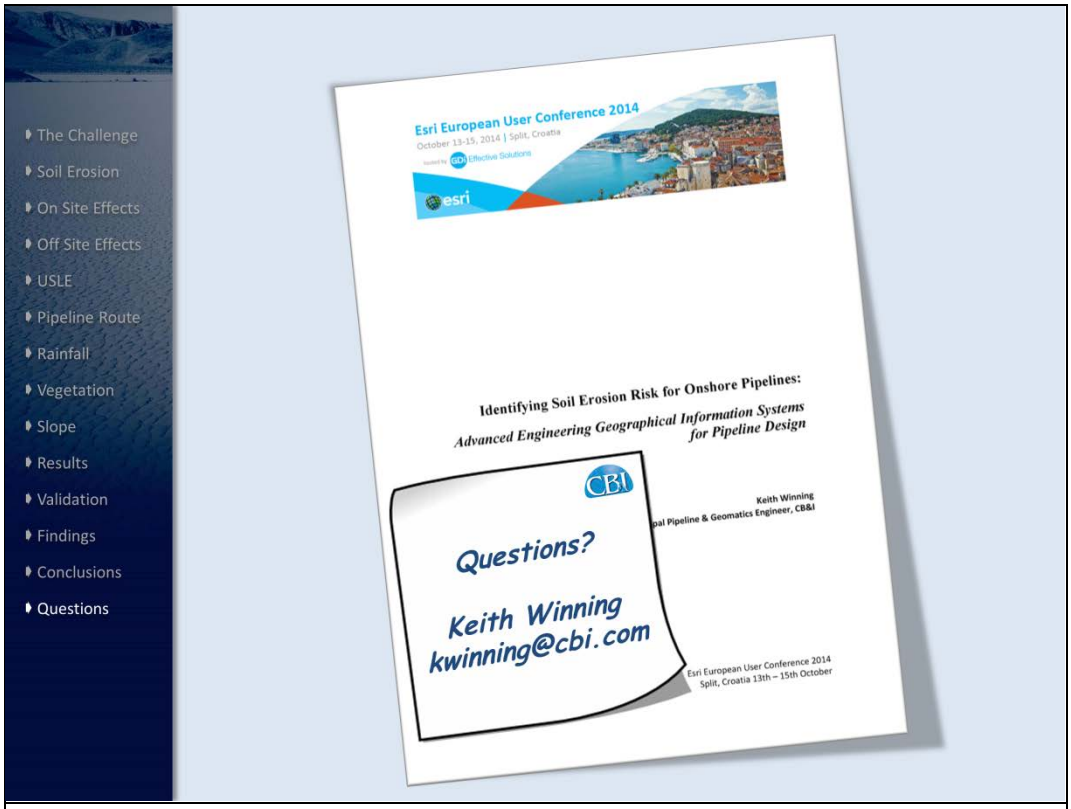
Slide 13



Slide 14



Slide 15



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