Using simulation to help assess CP current output of buried subsea pipeline anodes from field gradient measurements

Presented at the Marine Corrosion Forum meeting on 25th April 2017

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Introduction

- Subsea pipelines are often buried to provide greater protection from damage/impacts from vessels (eg fishing gear) and to provide greater stability. Such burial makes it more difficult to accurately assess Cathodic Protection levels, and anode activity.

Field gradient measurements, enhanced by simulation

- Field gradient measurements are an established method to estimate the outputs of sacrificial anodes, and provided the geometry of the relevant structure is simple, analytical methods usually provide adequate accuracy. However, if the electrical fields are distorted (for example as a result of complex geometry, local areas of coating damage, interference effects from nearby structures and so on), then the accuracy of analytical methods will degrade, and the calculated CP protection levels may be misleading.
- It then becomes advantageous to use numerical simulation to enhance interpretation of the measured data. The enhancement results from the ability of simulation to accurately represent the electrical fields regardless of the complexity (of geometry, coating damage, interference and so on).

Field gradient measurements, enhanced by simulation

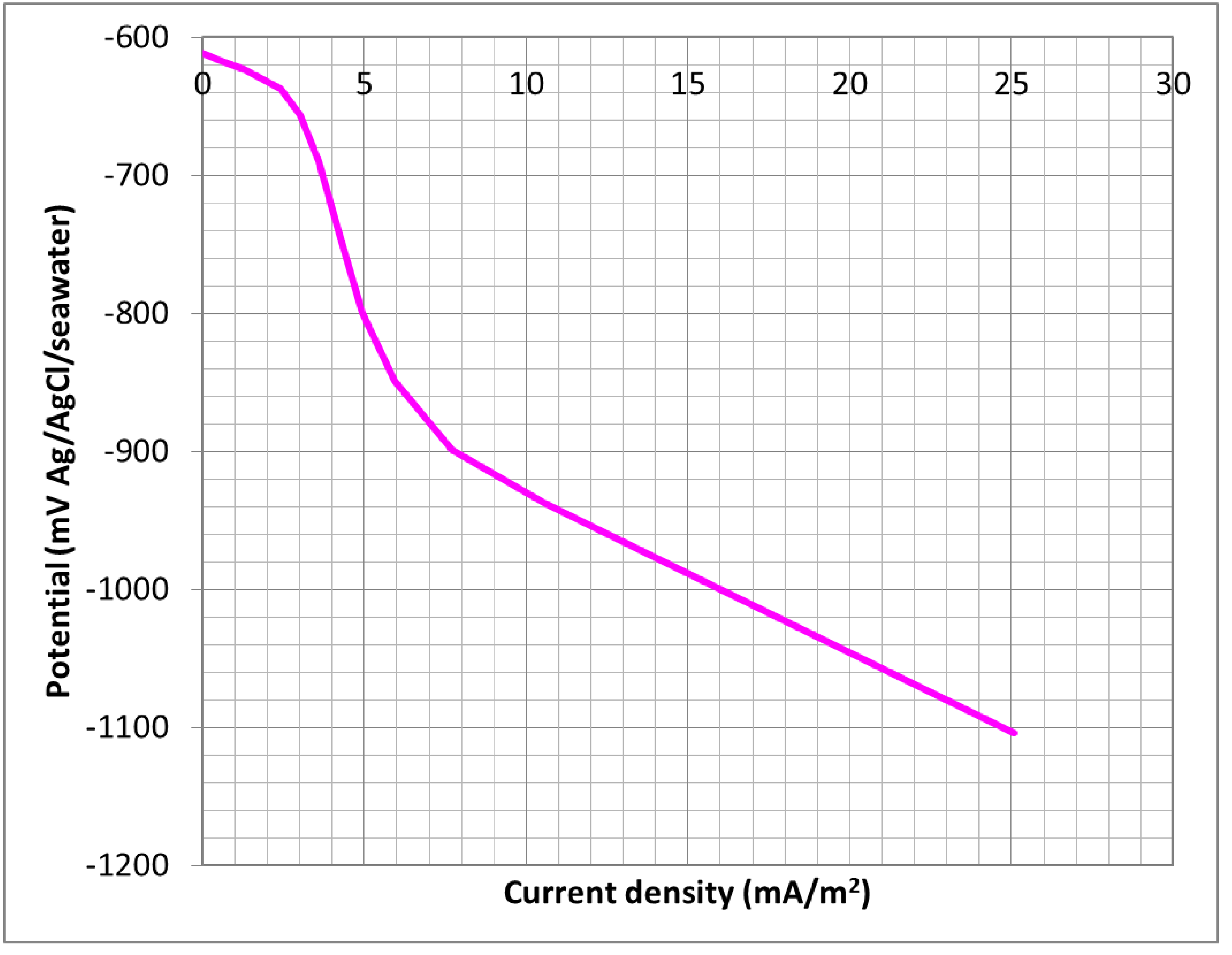
- In this presentation we investigate the application of simulation to determine anode output current in a buried pipeline, and use uncertainty of data (such as buried depth and position of the pipe) to attempt to identify the likely range of measurement which results from such variability.
- The presentation explains the approach used in the simulation work, including how a calibration stage can inform selection of a set of parameters which most accurately reproduces the observed field gradients.

Geometry details and properties

- Pipeline data:
  - Length ~ 9800m
  - Outer diameter 600mm
  - Resistance along pipe length 0.0000086 Ohms/m
  - Either buried at 2m below seabed (to centre line), or at 4m buried depth, or above the seabed
- Water depth 100m
- Water resistivity 30 Ohm-cm
- Seabed resistivity 150 Ohm-cm
- Anode data:
  - Length 0.8m
  - Outer diameter 600mm
  - Mass 190kg
  - Utilisation factor 0.8
  - Material efficiency 1500Ah/kg
- Anode spacing ~ 615m

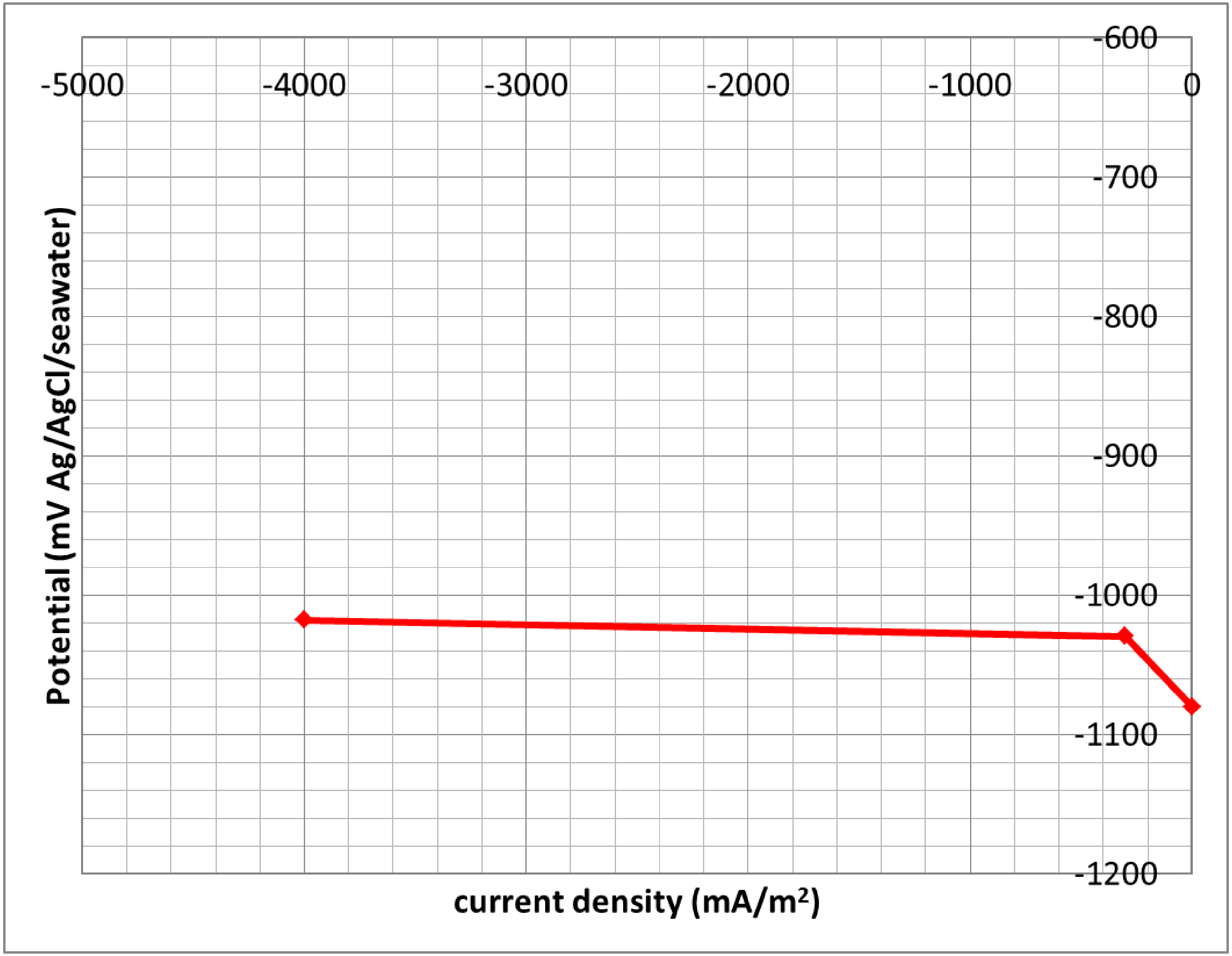
Polarisation curves

- The polarisation curve applied to the pipeline was as shown here:



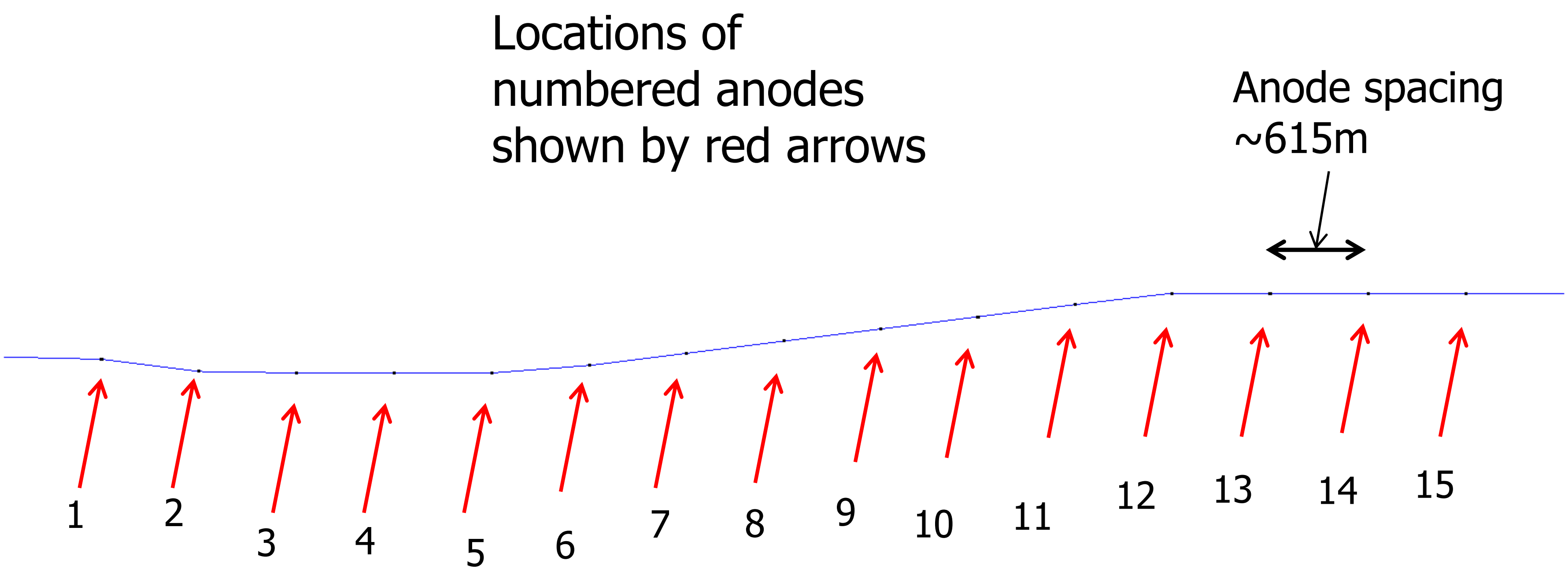
Polarisation curves

- The polarisation curve applied to the anodes was as shown here:



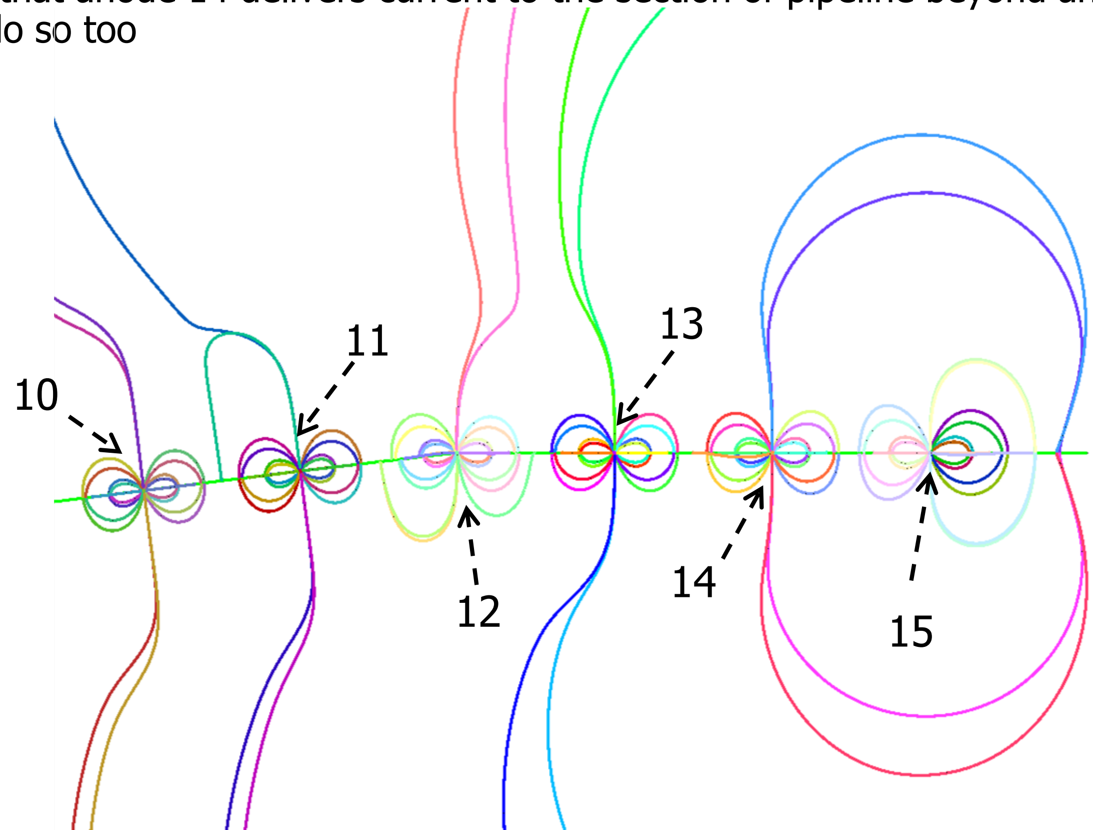
Plan view showing anode locations

- Note there are no anodes at the ends



Flowlines showing path of current from positions near the anodes

- One way of viewing the effects on electric fields around the anodes is to view flowlines which show where current from the anodes goes. The flowlines are created, starting from selected positions, which in this work were positioned around the top half of the anodes.
- In this plan view (which shows flowlines for anodes 10 to 15 for the case with the pipeline buried 2m):
  - Flowlines are close to symmetric for anodes 15 and 14
  - The bend in the pipeline causes asymmetry of the flowlines for anodes 10 to 13
  - It is clear that anode 14 delivers current to the section of pipeline beyond anode 15, but in fact anodes 10 to 13 do so too



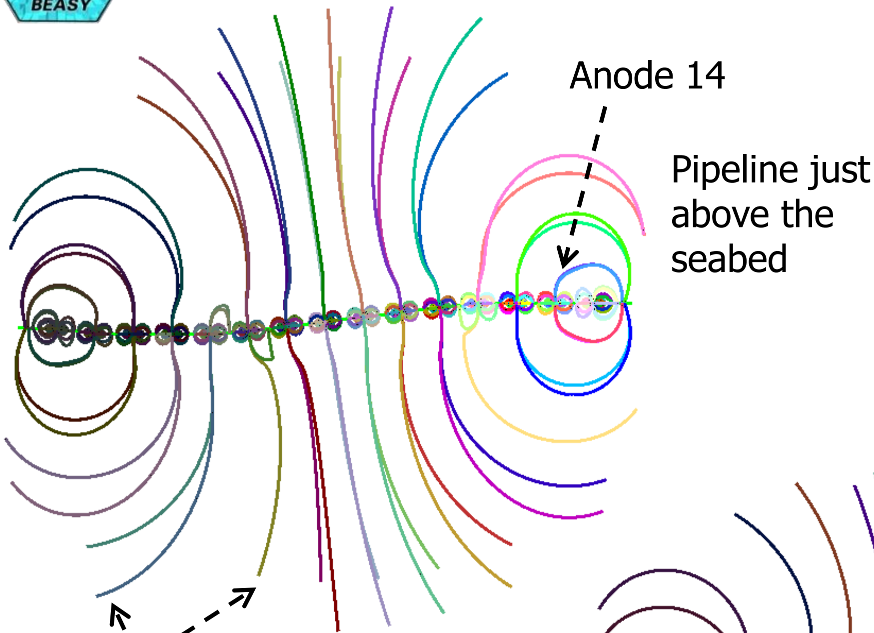
Flowlines showing path of current from positions near the anodes

- To help viewing of the flowlines, this video shows flowlines for anodes 14 and 15

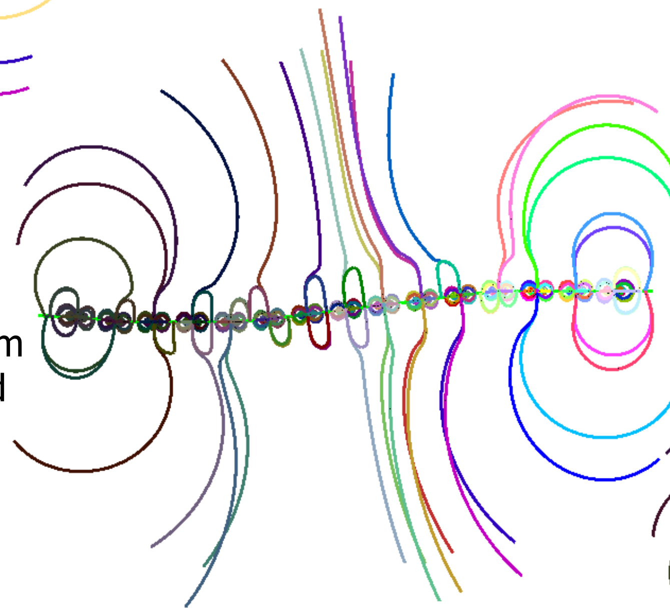
- The following slides compare the directions of electric field for the cases with the pipeline:
  - Just above the seabed
  - Buried at 2m below the seabed
  - Buried at 4m below the seabed

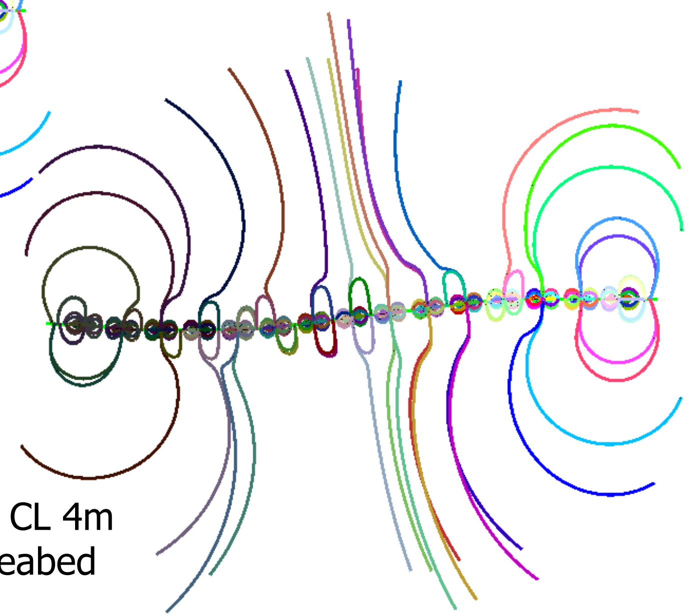
Plan views of flowlines for all anodes, showing effects of buried depth

- Some flowlines extend further when the pipeline is buried (eg look at the cyan line extending from anode 14)
- Because there are no anodes at the ends of the pipeline, current flows from all anodes to the ends of the pipeline

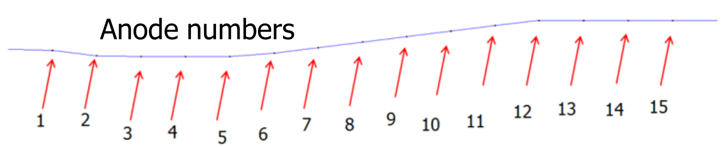


Some flowlines are not tracked to their eventual destination

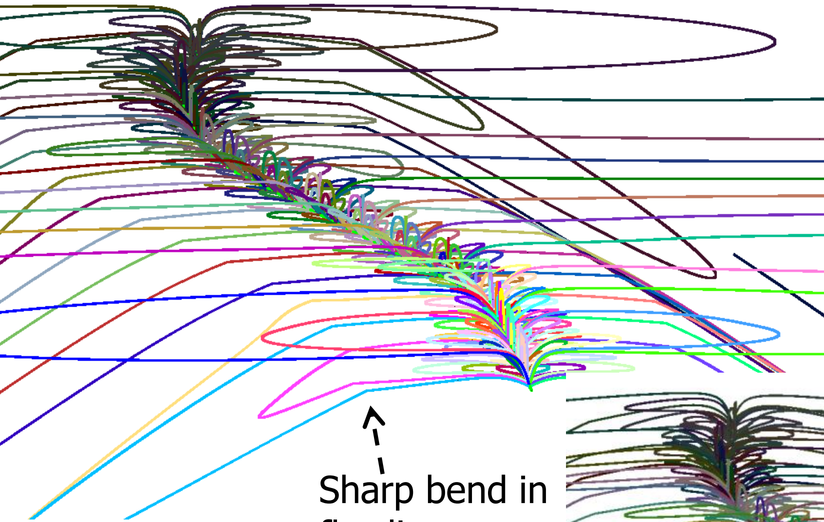




Scale is the same in each view



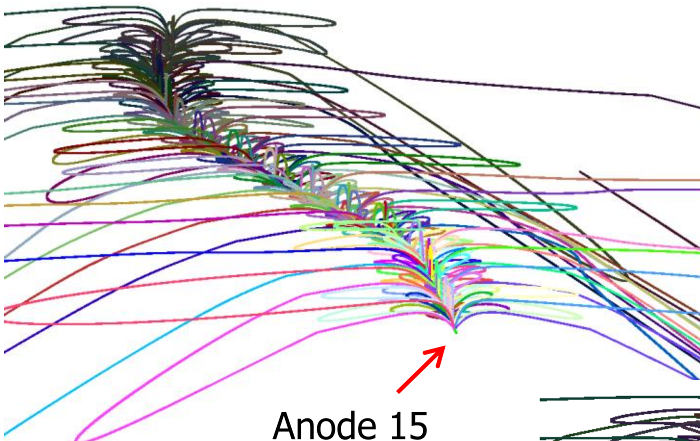
Isometric views of flowlines, showing effects of buried depth



Pipeline just above the seabed

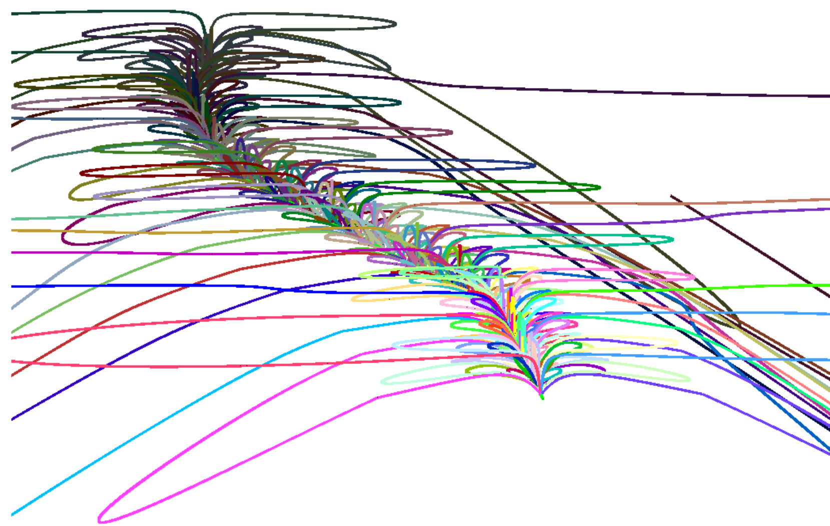
Sharp bend in flowline

- Flowlines bend sharply when they pass through the seabed



Pipeline CL 2m below seabed

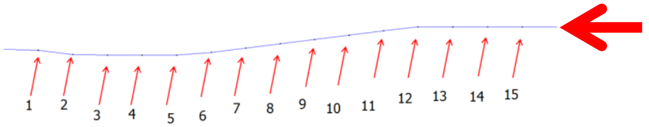
Anode 15 this end

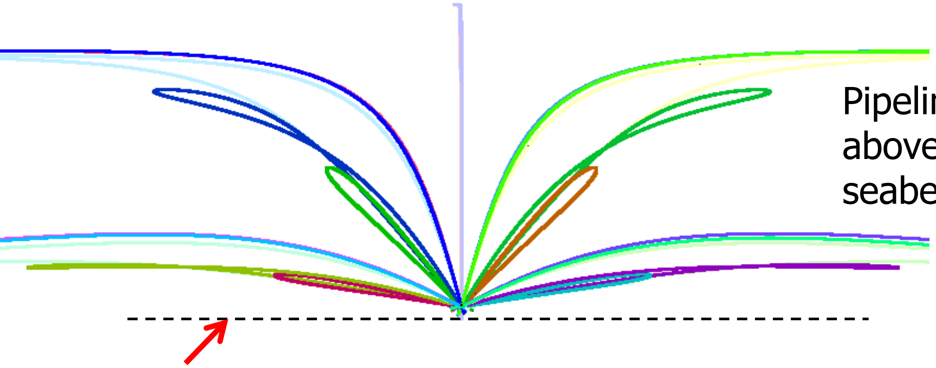


Pipeline CL 4m below seabed

End views of flowlines, showing effects of buried depth

View is of this end



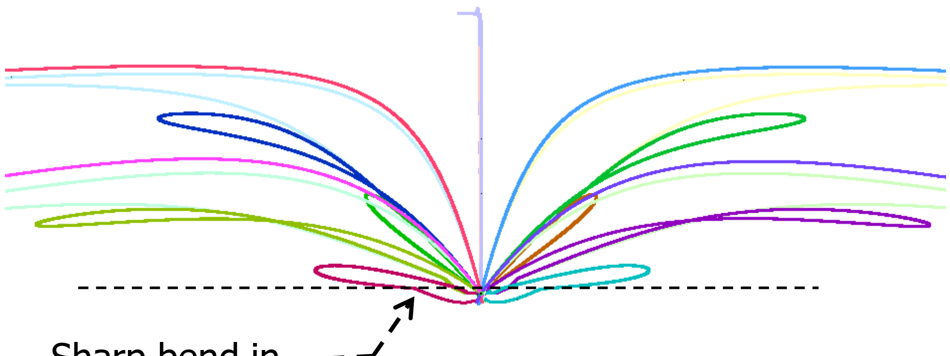


Pipeline just above the seabed

Position of seabed

- Flowlines bend gradually as they approach the sea surface

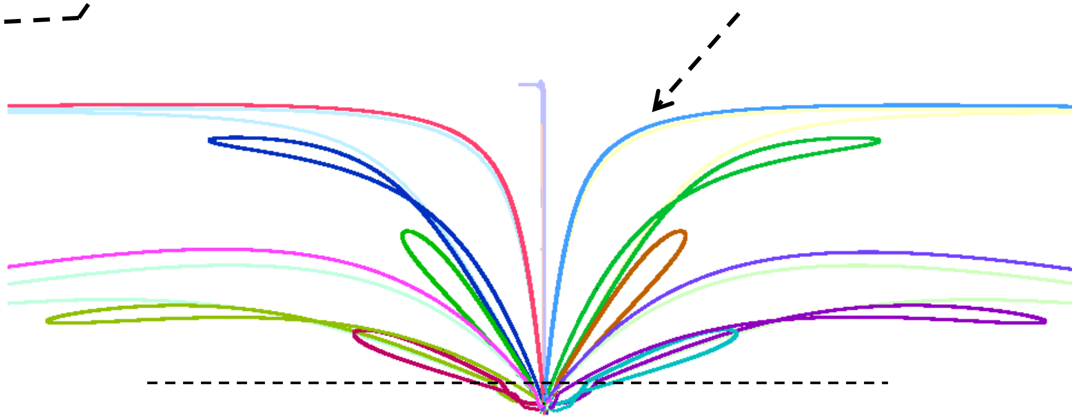
Pipeline CL 2m below seabed



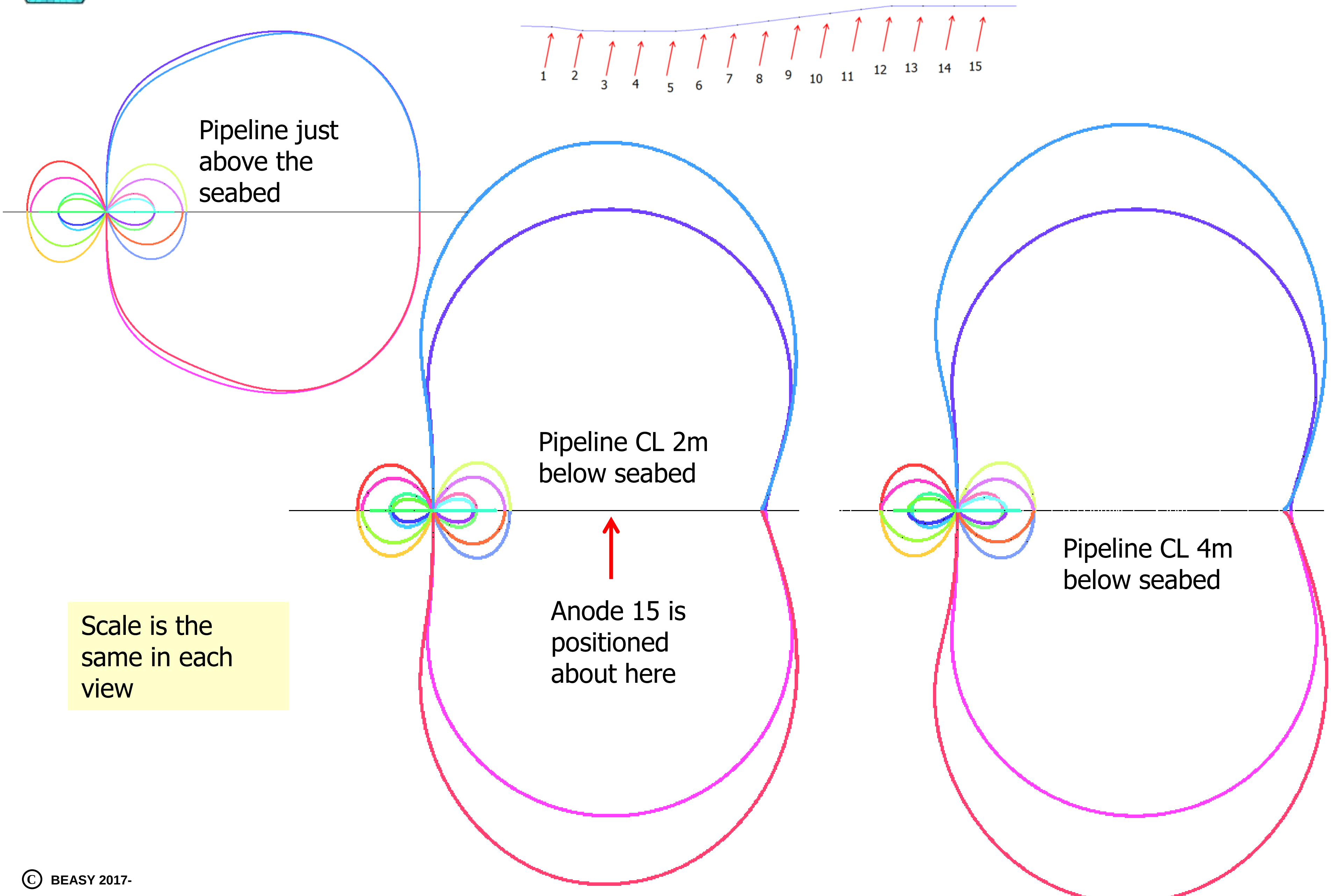
Sharp bend in flowline

Gradual bend in flowline

Pipeline CL 4m below seabed

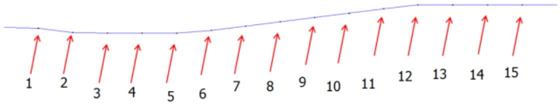


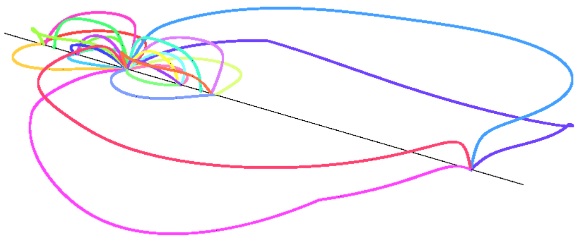
Plan views of flowlines for anode 14, showing effects of buried depth



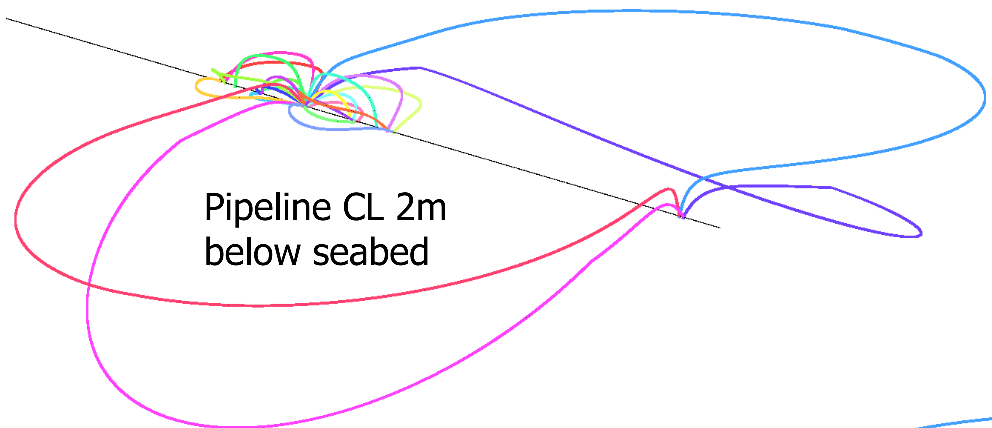
Scale is the same in each view

Isometric views of flowlines for anode 14, showing effects of buried depth

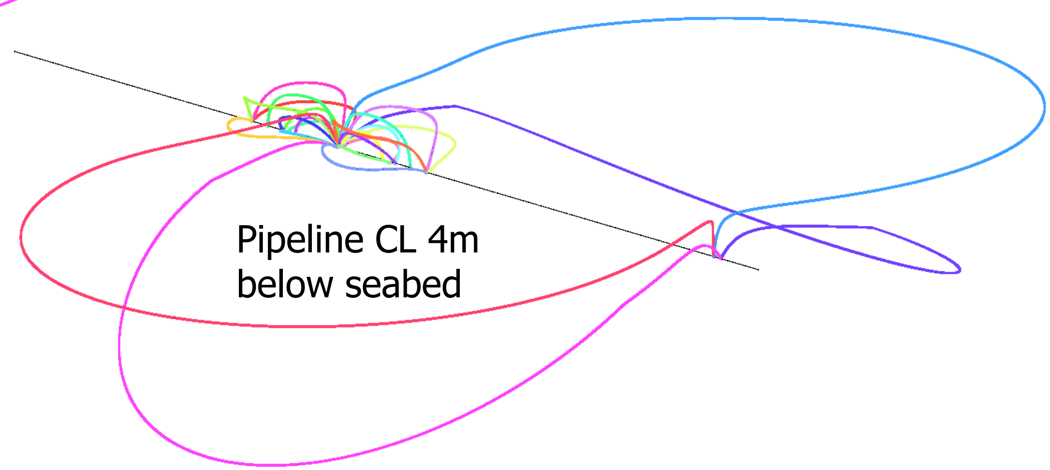




Pipeline just above the seabed



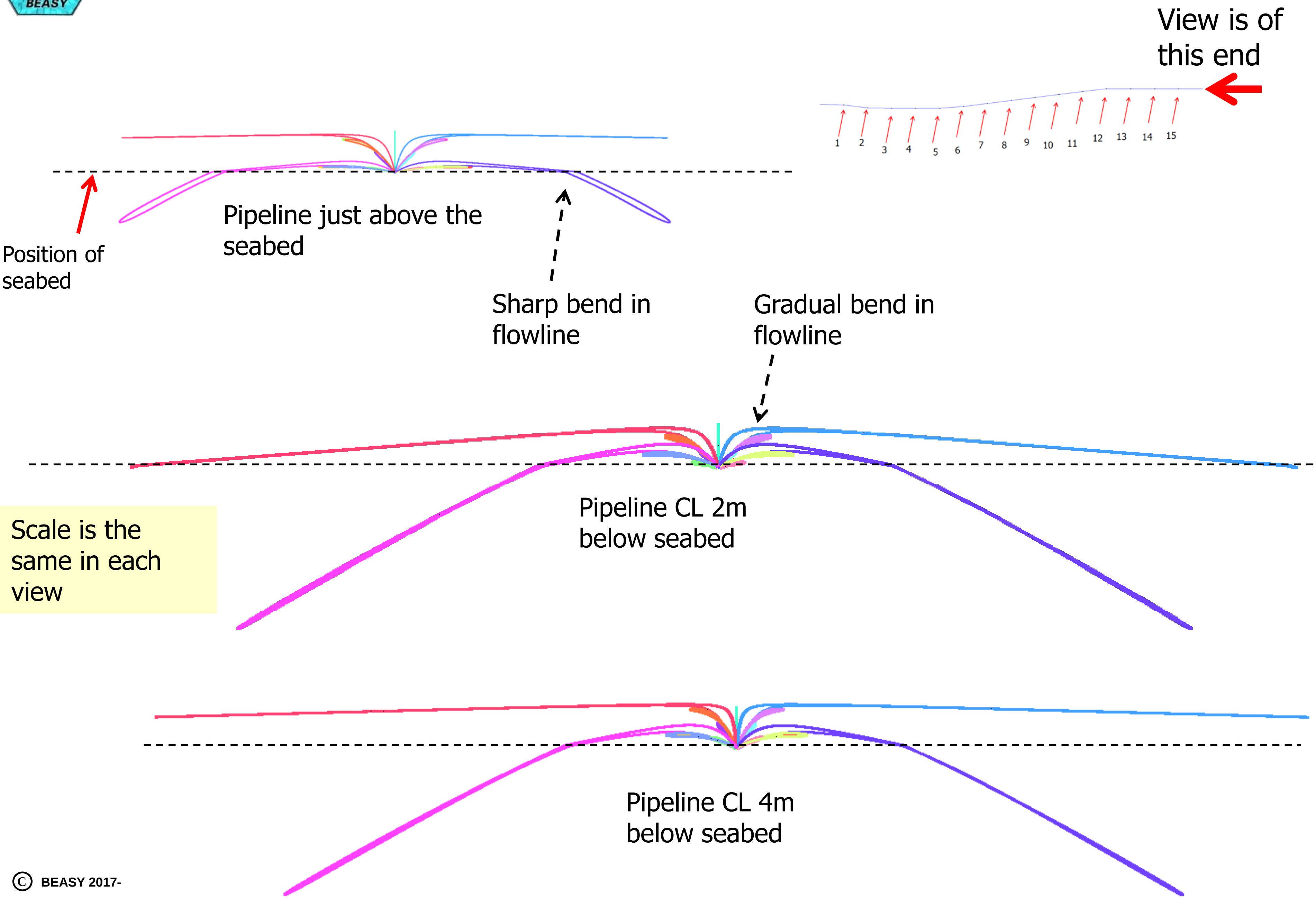
Pipeline CL 2m below seabed



Pipeline CL 4m below seabed

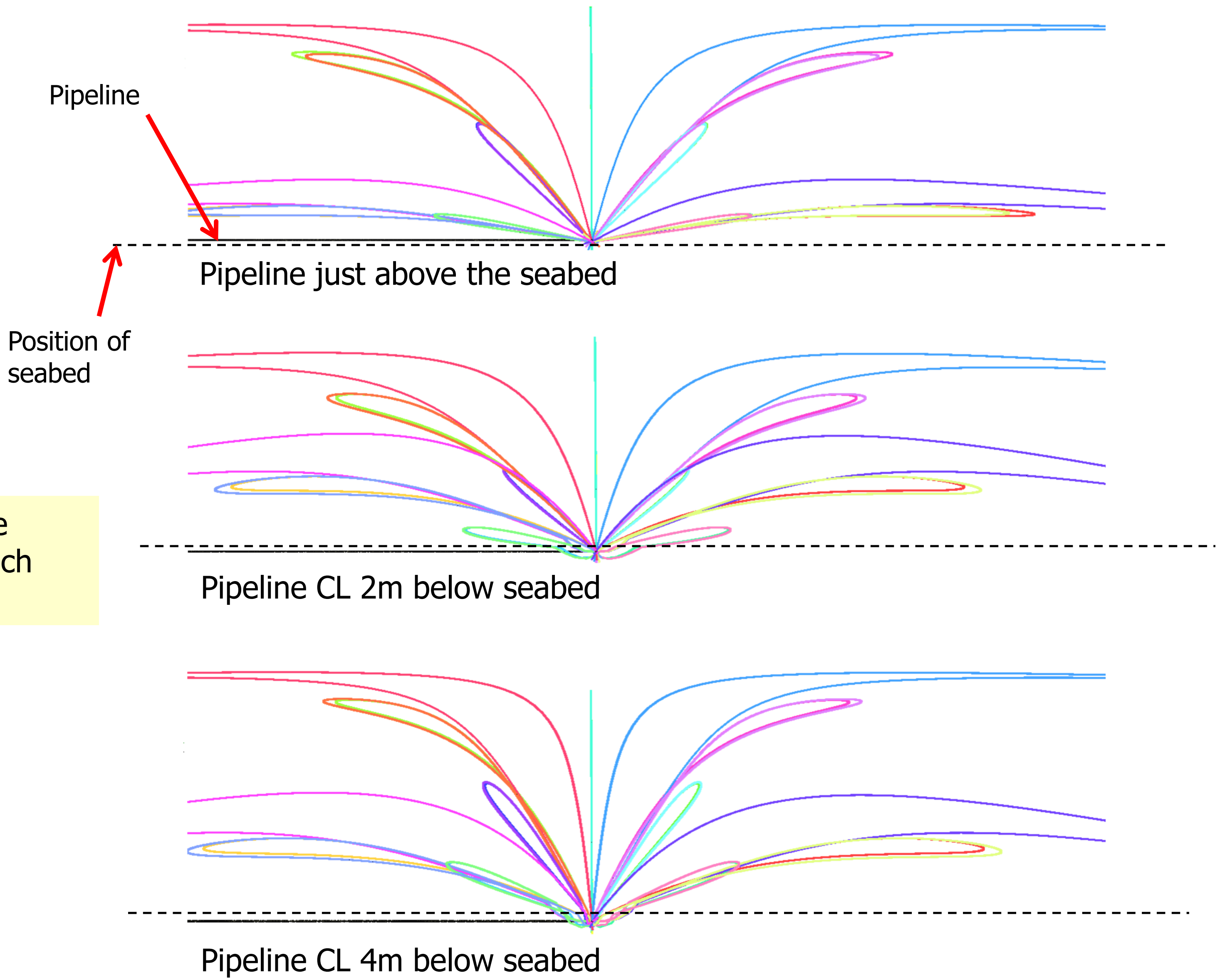
Scale is the same in each view

End views of flowlines for anode 14, showing effects of buried depth



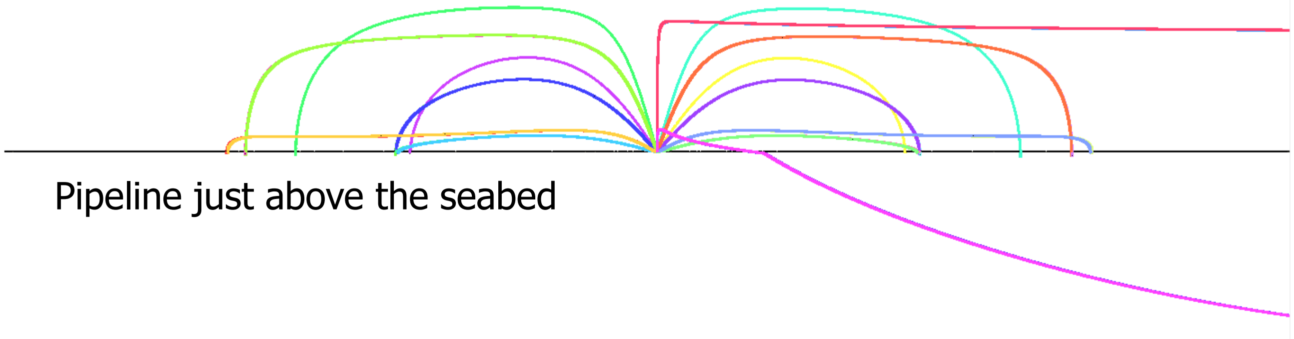
Scale is the same in each view

Close-up end views of flowlines for anode 14, showing effects of buried depth

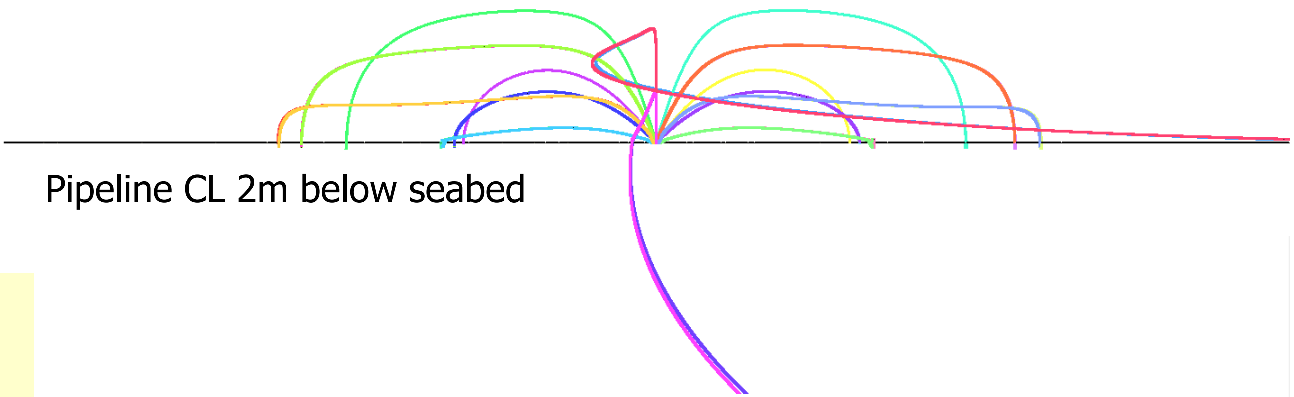


Scale is the same in each view

Side views of flowlines for anode 14, showing effects of buried depth

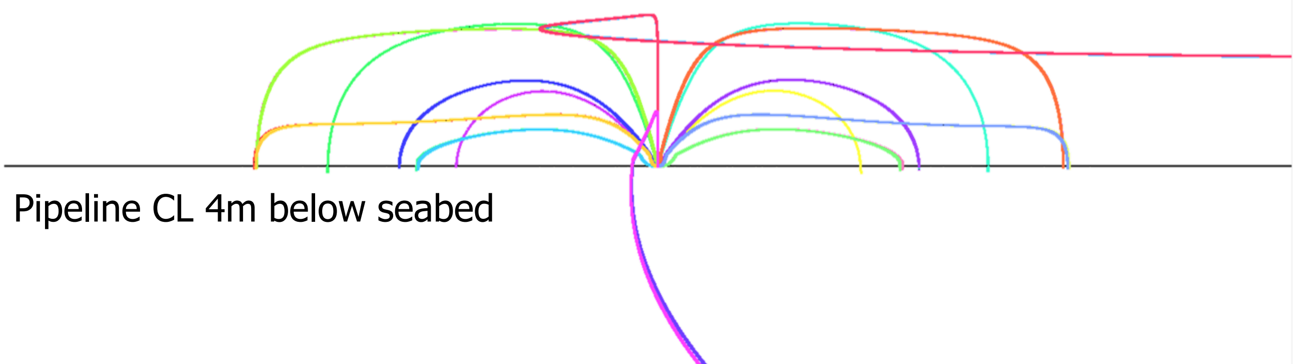


Pipeline just above the seabed



Pipeline CL 2m below seabed

Scale is the same in each view



Pipeline CL 4m below seabed

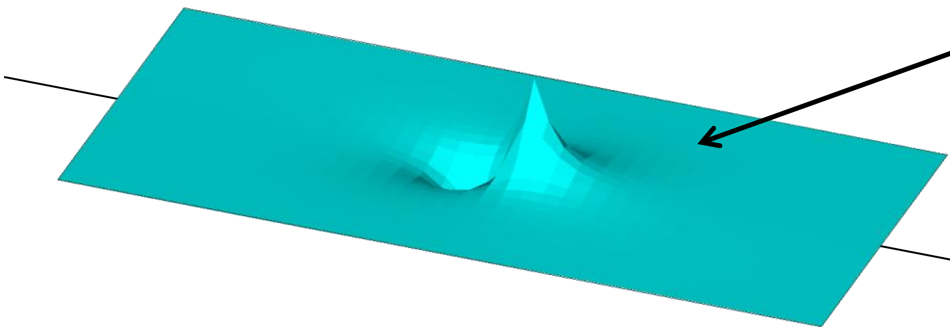
Electric field (field gradient)

- It is clear from the previous slides that the way in which the electric field varies is complex

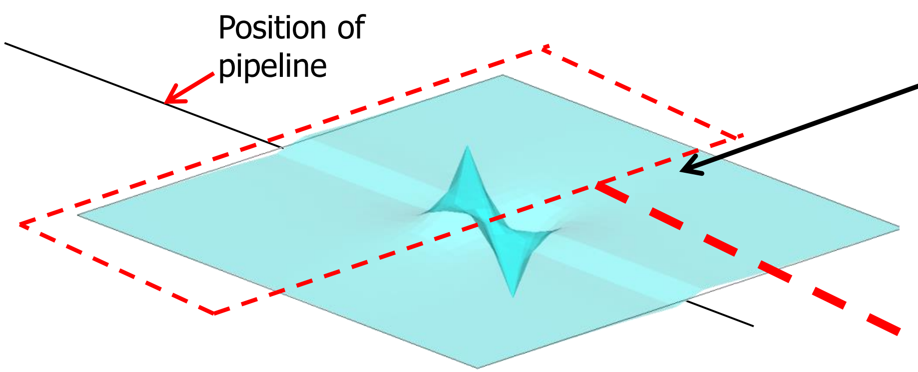
- The following slide shows "surfaces" indicating magnitude of electric field components in directions:
  - along the pipeline (E to W direction)
  - across the pipeline (transverse, or N to S direction)
  - vertically down

- The electric field shown in these result surfaces was calculated at 90m below the sea surface (ie 10m above the seabed) for the case with the pipe buried at 2m below seabed…

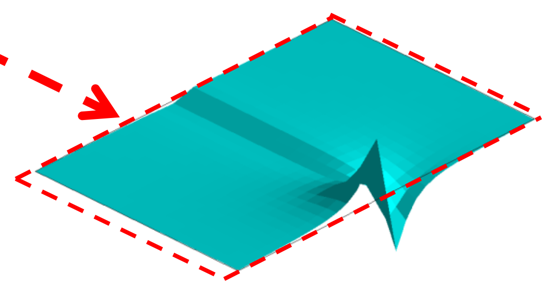
Surfaces showing magnitude of electric field at 90m below sea surface (ie 10m above seabed), for the case with the pipeline at 2m below seabed

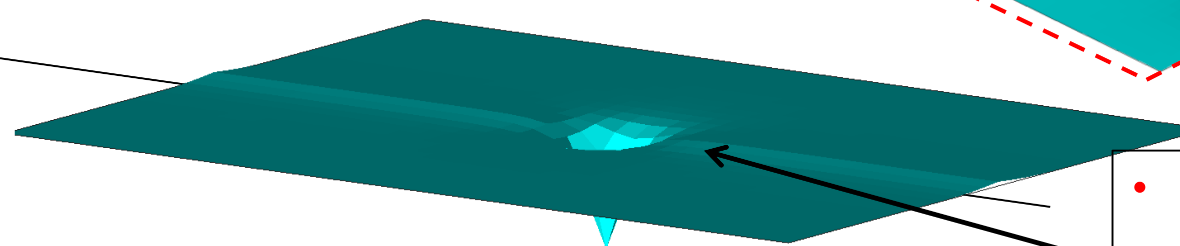


- Electric field (E) in horizontal direction along the pipeline:
  - has positive and negative peaks at positions above the pipeline but some distance away from the anode
  - is zero above the anode



- Electric field (E) in horizontal direction across the pipeline:
  - has positive and negative peaks at positions to either side of, but some distance away from the anode
  - is zero above the anode

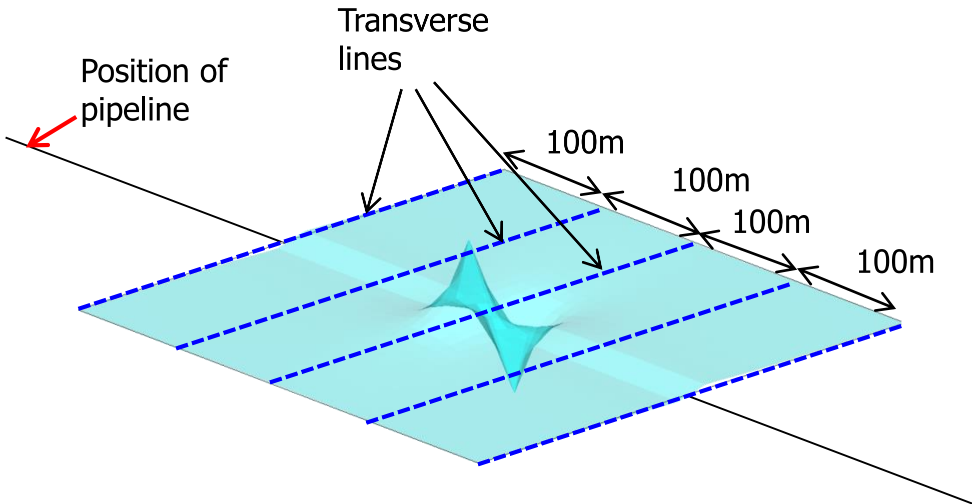




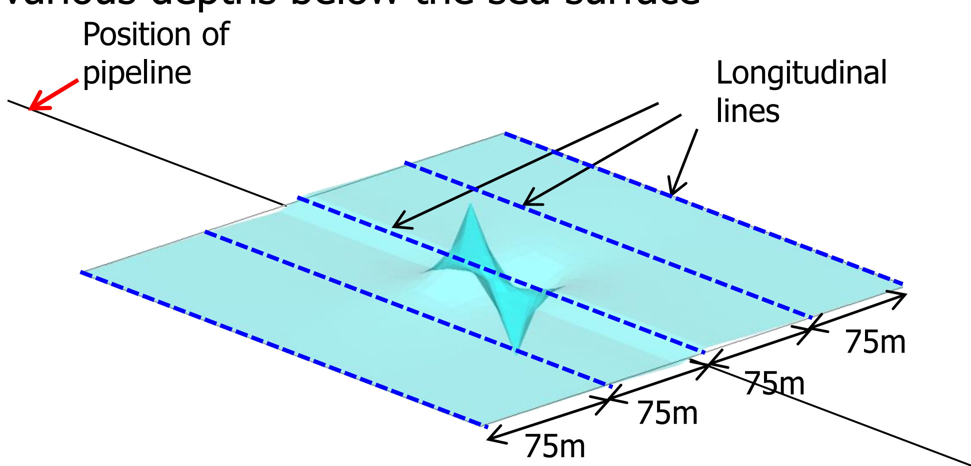
- Electric field (E) in vertical direction:
  - has a single peak at position above the anode

Graphs of electric field

- Following slides show variation of electric field along lines such as those shown below:
  - Transverse lines at 0m, 100m and 200m away from the anode (in East or West direction), and at various depths below the sea surface

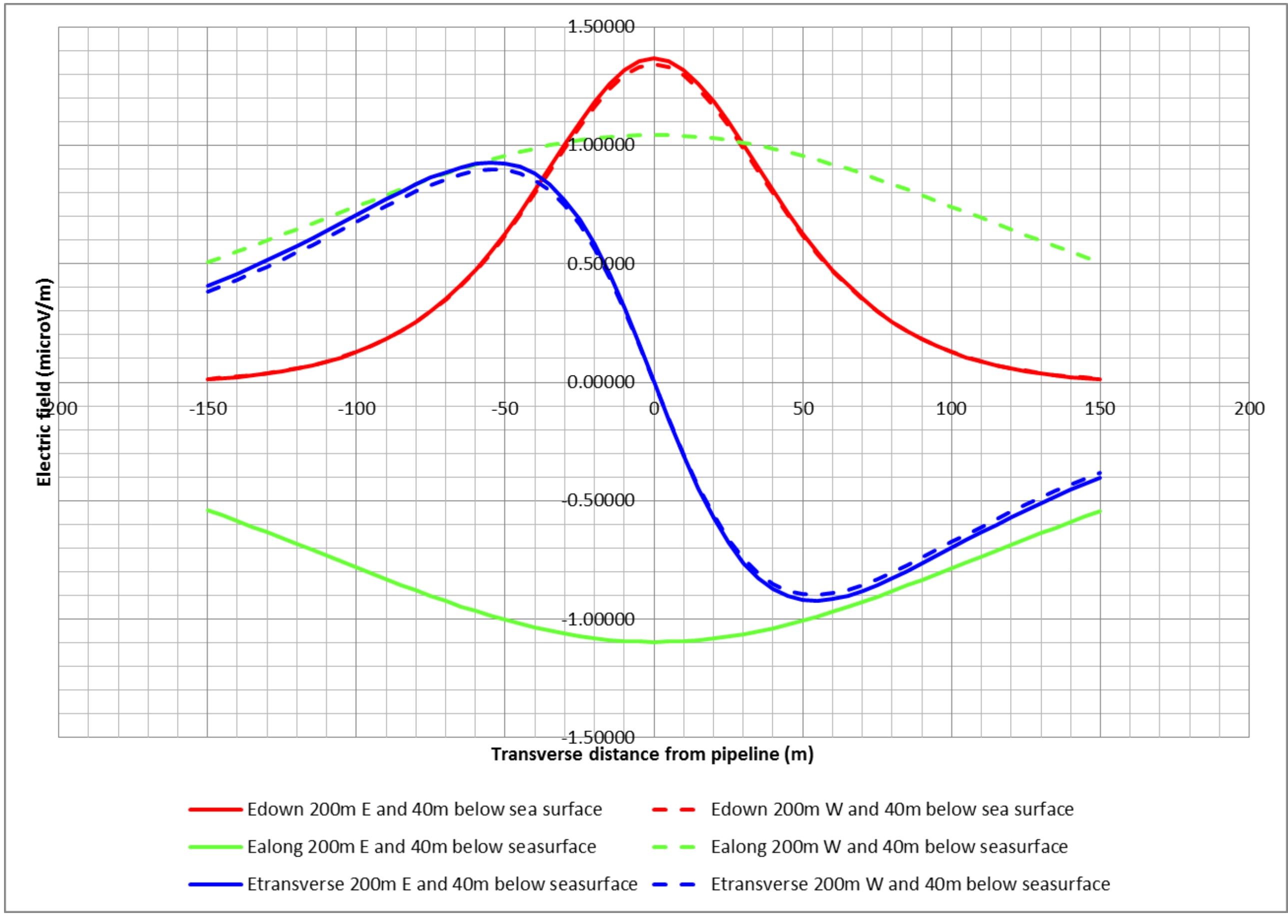


  - Longitudinal lines at 0m, 75m and 150m away from the pipeline (in North or South direction), and at various depths below the sea surface



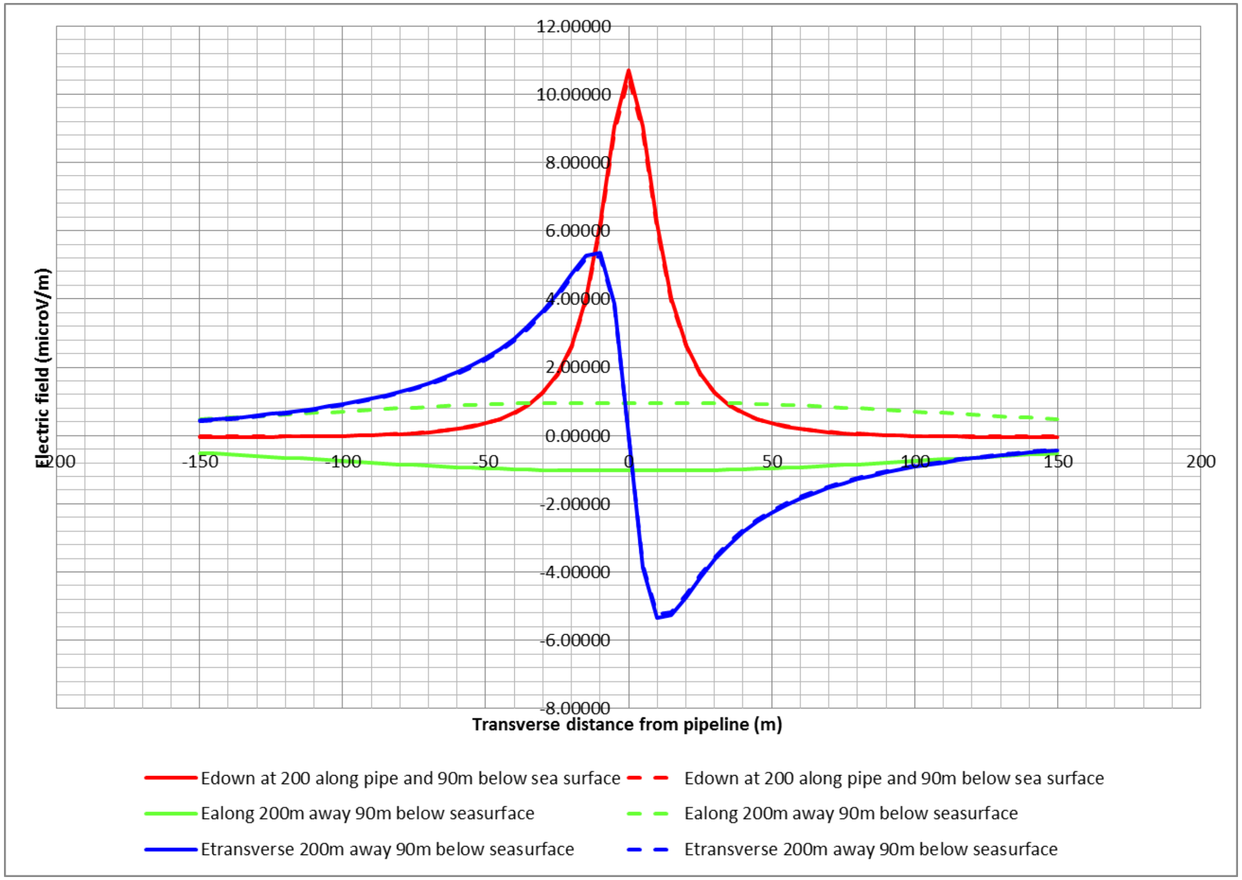
Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

- Along a transverse line at 40m below sea surface and 200m East and West of anode 13:
  - Vertical and transverse electric field is almost the same at 200m East as at 200m West of the anode
  - Longitudinal electric field ("along") at 200m East is the reverse of the field at 200m West of the anode
  - At 200m away from the anode the electric field at 40m below sea surface (ie 60m above seabed) is very small (maximum component magnitude is about 1.4 microV/m)
  - The biggest component is vertical



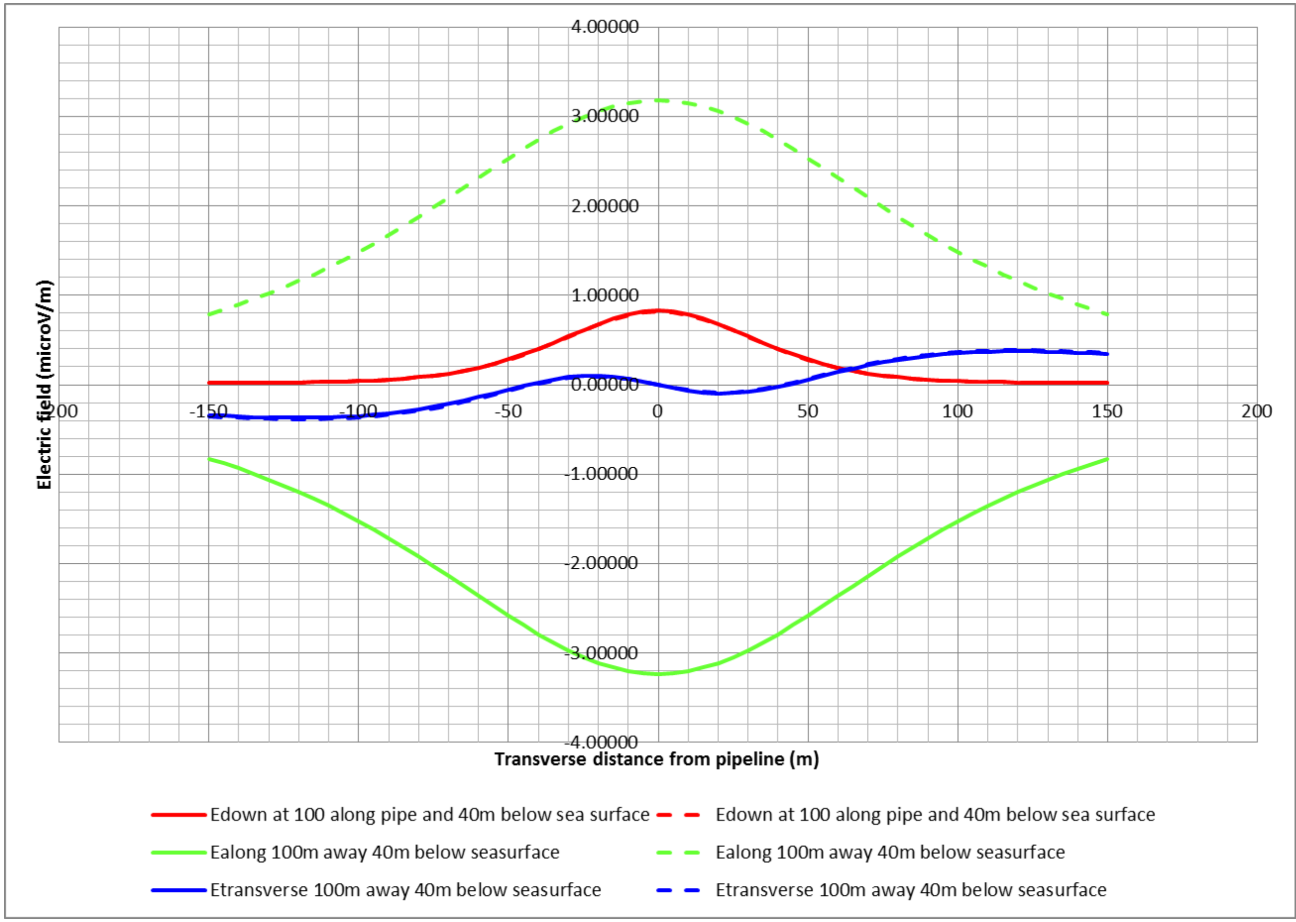
Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

- Along a transverse line at 90m below sea surface and 200m East and West of anode 13:
  - The patterns of variation are the same as at 40m depth
  - But the magnitude of electric field is bigger (maximum component magnitude is about 10.5 microV/m)



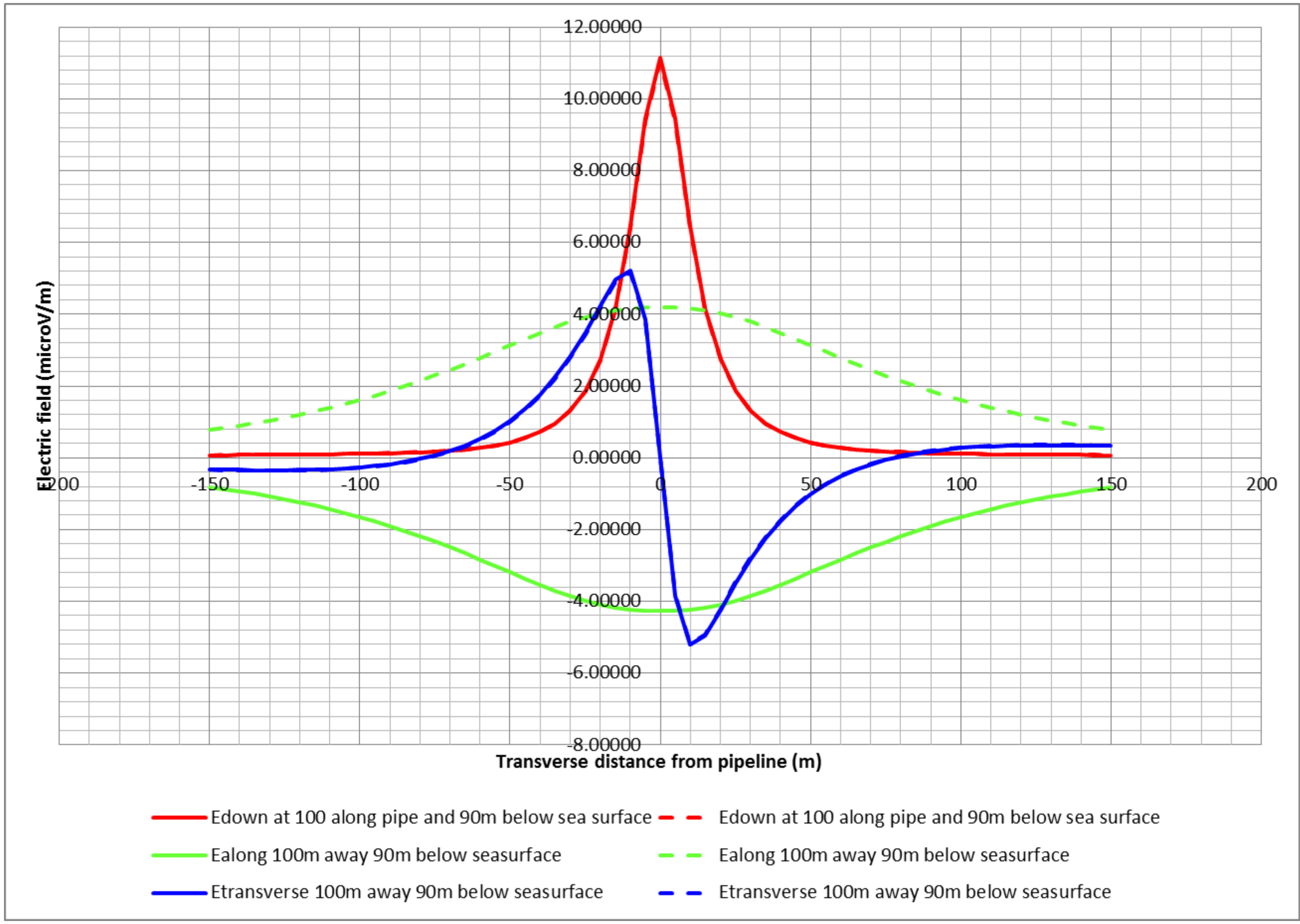
Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

- Along a transverse line at 40m below sea surface and 100m East and West of anode 13:
    - The patterns of variation are the same as at 200m away
    - However the biggest component is now *along* the pipeline, with magnitude about 3.2 microV/m



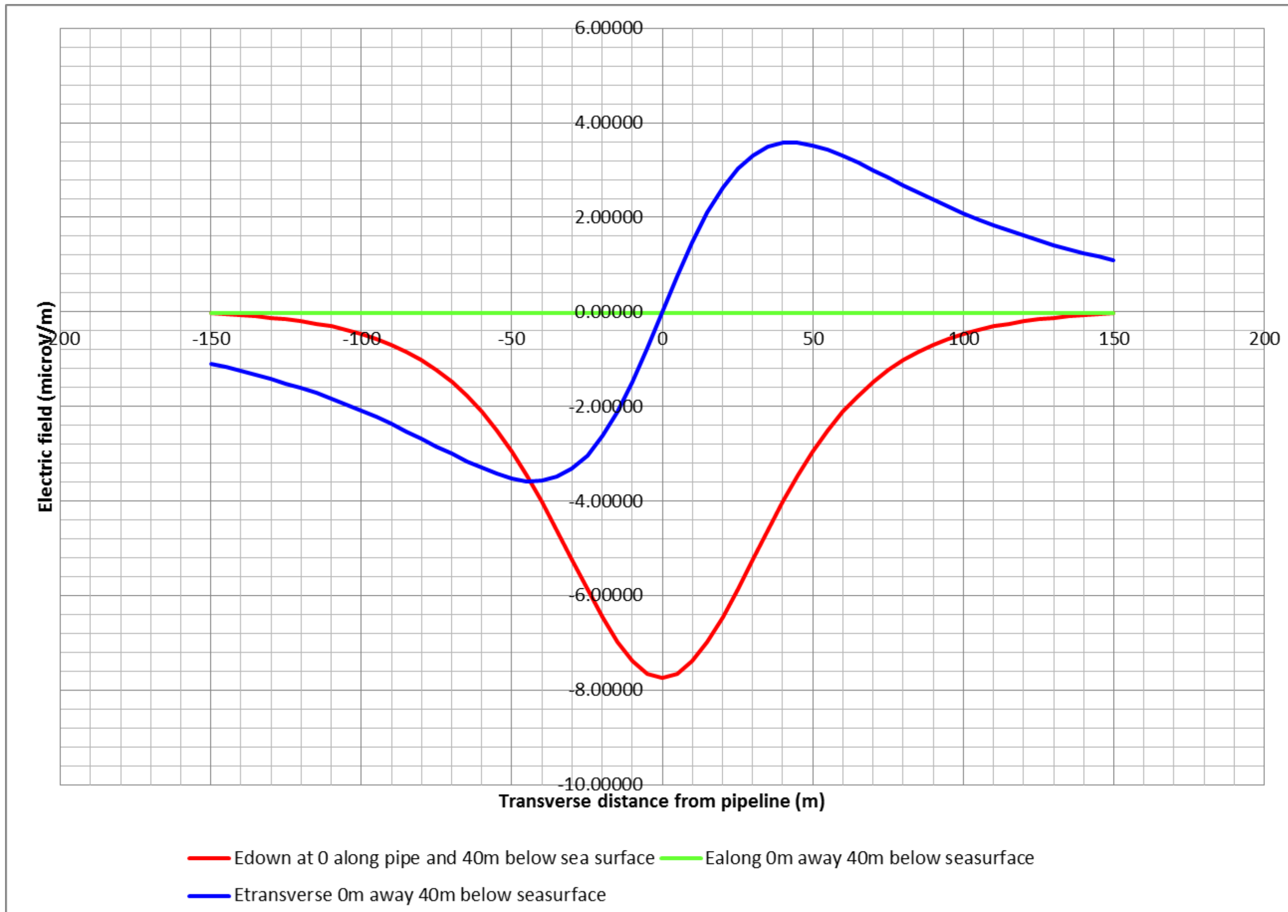
Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

- Along a transverse line at 90m below sea surface and 100m East and West of anode 13:
  - The patterns of variation are the same as at 200m away
  - The biggest component is vertical, with magnitude about 11.0 microV/m



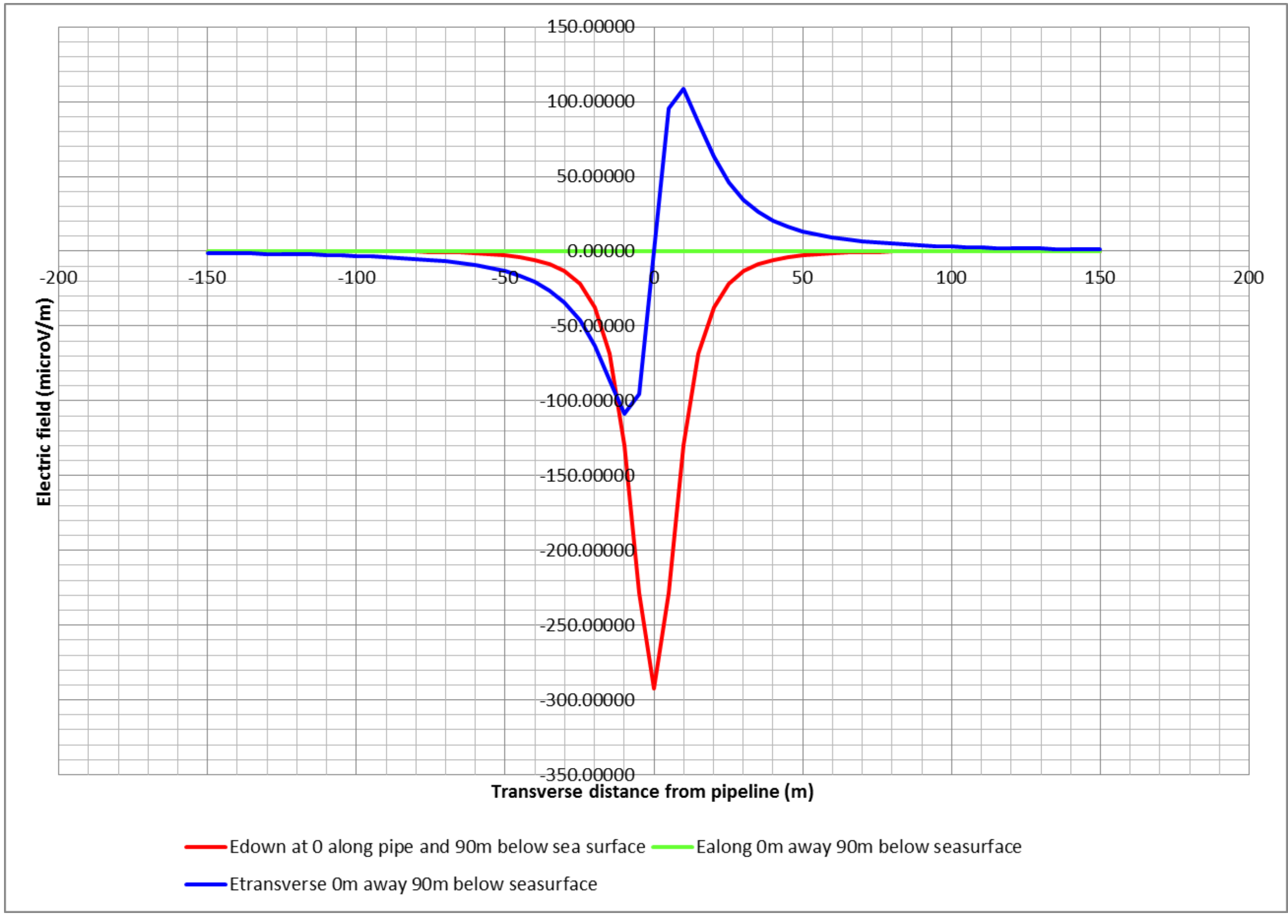
Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

- Along a transverse line at 40m below sea surface and immediately above the anode:
  - The component *along* the pipeline is close to zero
  - The vertical component of electric field is the opposite sign of that at 100m/200m E or W of the anode (indicating that current is flowing upwards, out of the anode)
  - The biggest component is vertical, with magnitude about 8.0 microV/m



Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

- Along a transverse line at 90m below sea surface and immediately above the anode:
  - The component *along* the pipeline is close to zero
  - The vertical component of electric field is the opposite sign of that at 100m/200m E or W of the anode (indicating that current is flowing upwards, out of the anode)
  - The biggest component is vertical, with magnitude about 290.0 microV/m

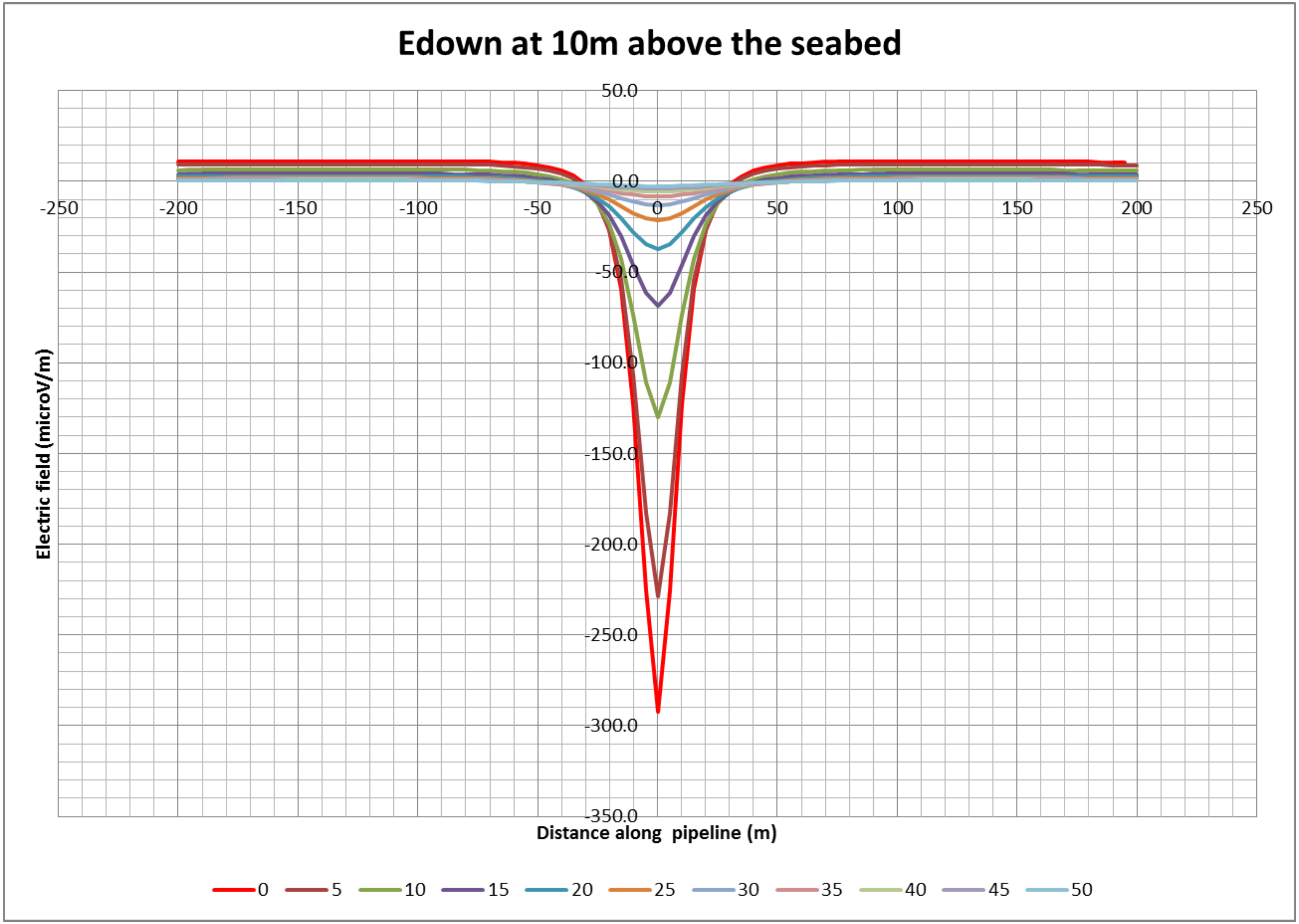


Graphs of electric field at positions near anode 13, for the case with the pipeline at 2m below seabed

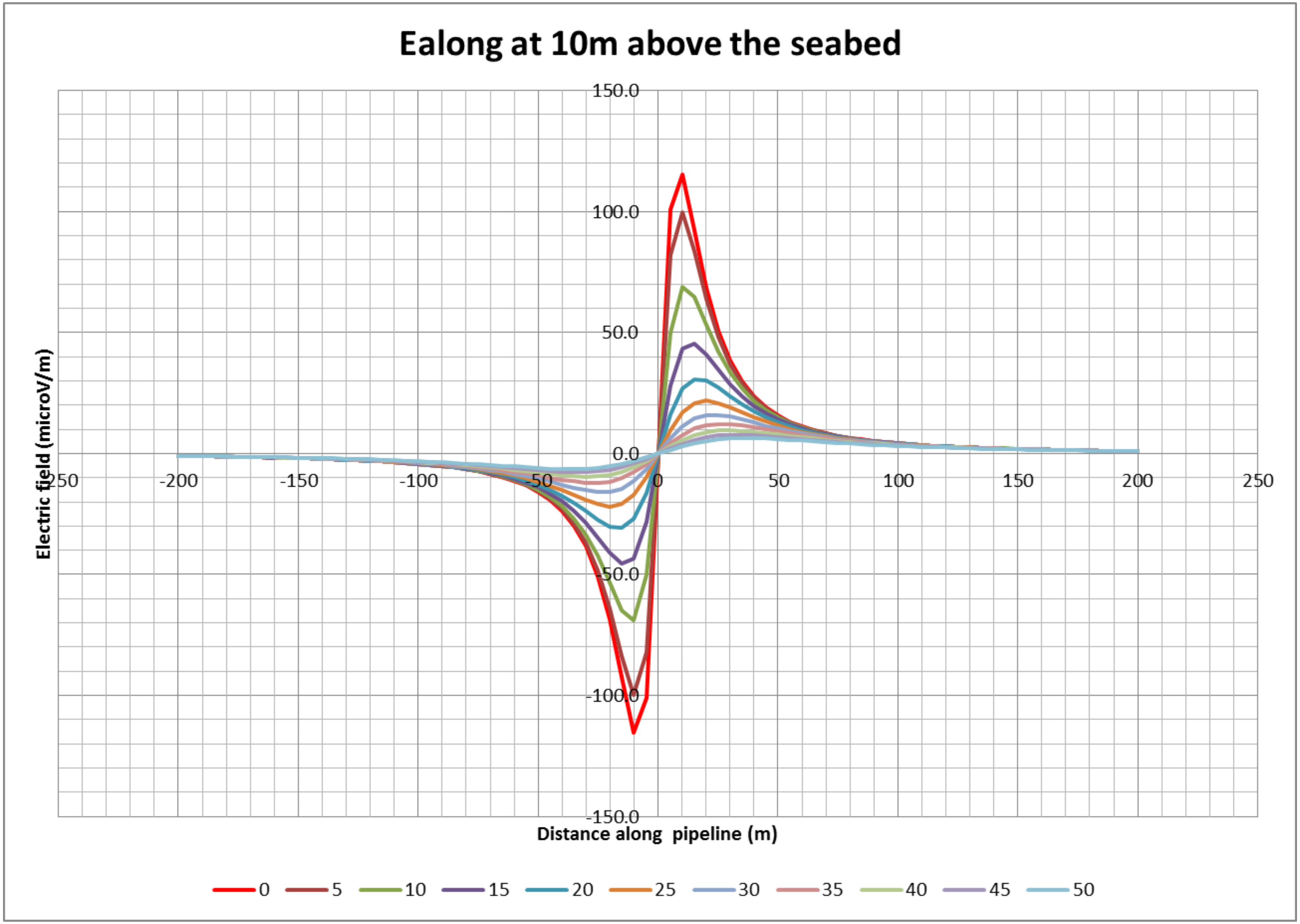
- The following figures show variation of the three components of electric field:
  - Along a series of longitudinal lines at 10m above the seabed (ie depth 90m below the sea surface)
  - With the lines at various distances (from 0 to 50m) sideways from the pipeline
- These lines represent paths (of the measurement device) with some sideways positioning error…
- Such families of curves could possibly be used to:
  - Identify the sideways positioning error (for example by using the sign of the transverse electric field)
  - Estimate the vertical electric field immediately above the anode

- In this case the anode output was 1.14 Amps

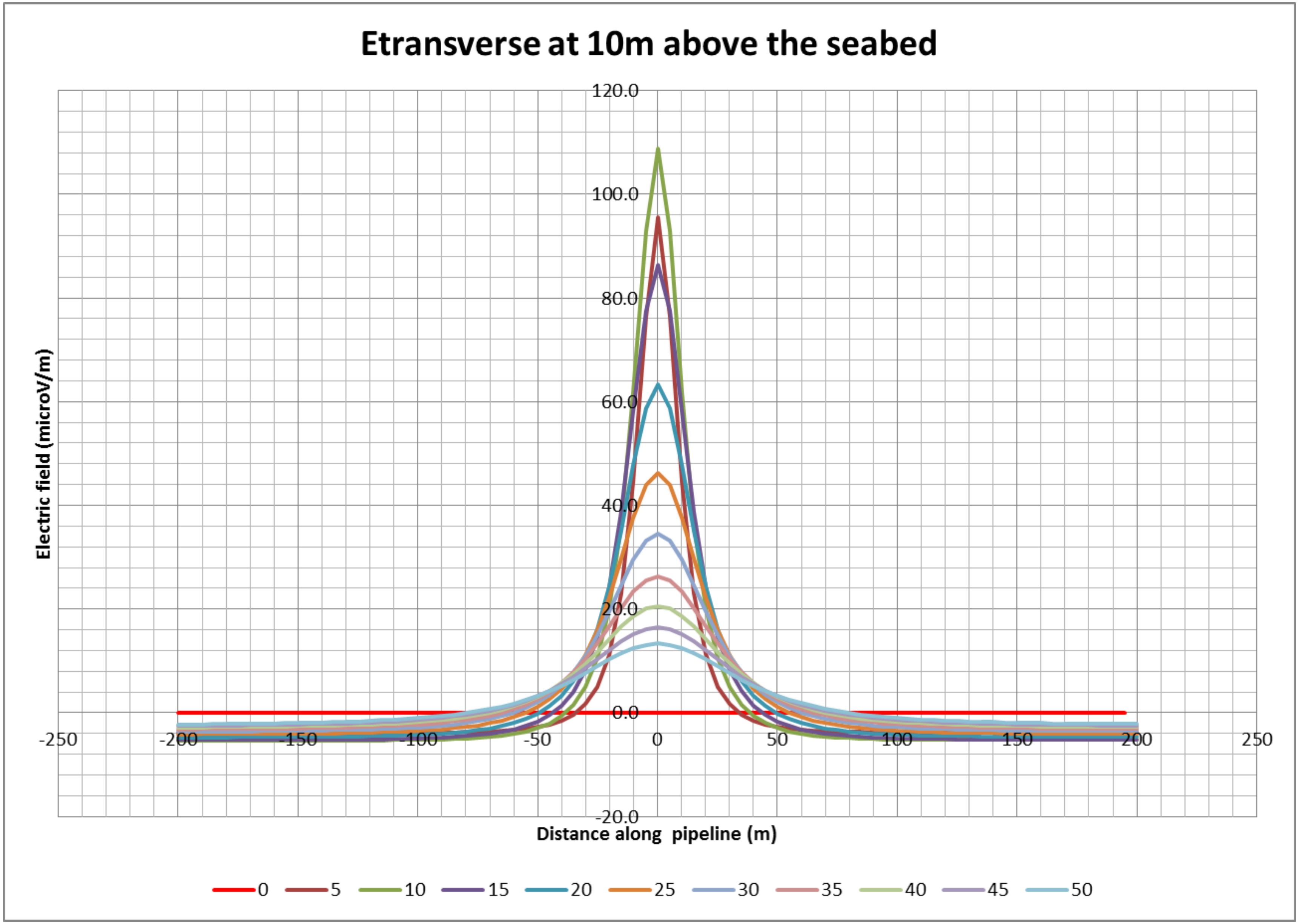
Graph of vertical electric field along lines parallel to the pipeline but offset sideways by from 0 to 50m, for the case with the pipeline at 2m below seabed



Graph of longitudinal electric field along lines parallel to the pipeline but offset sideways by from 0 to 50m, for the case with the pipeline at 2m below seabed



Graph of transverse electric field along lines parallel to the pipeline but offset sideways by from 0 to 50m, for the case with the pipeline at 2m below seabed



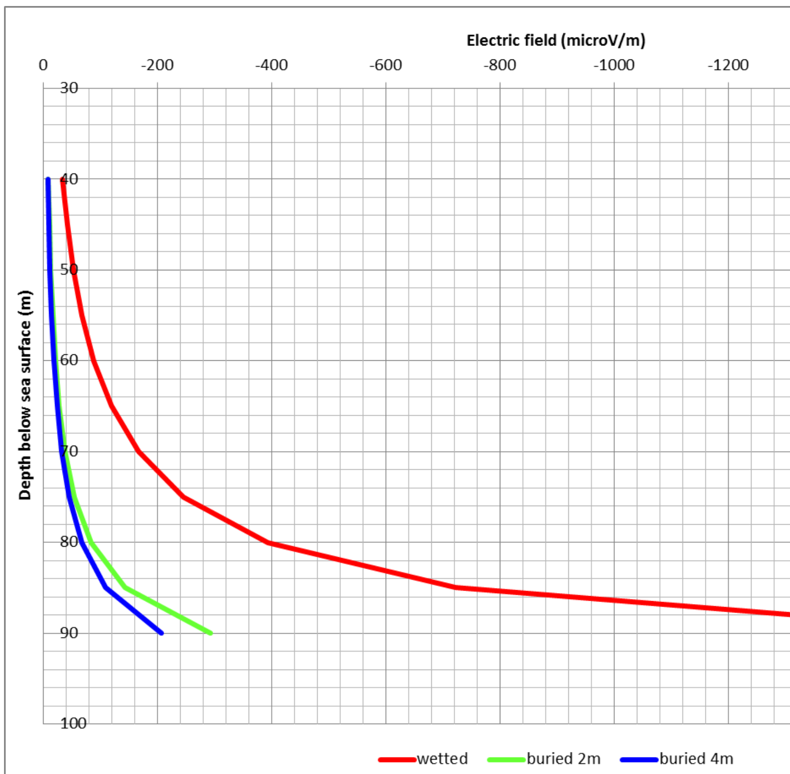
Variation of vertical electric field above anode 13, for the case with the pipeline at 2m below seabed

- This curve shows the variation of vertical electric field with depth below the sea surface
  - The magnitude of the field increases very rapidly in the bottom few metres, and confirms that any measurement device should be positioned as close as possible to the seabed

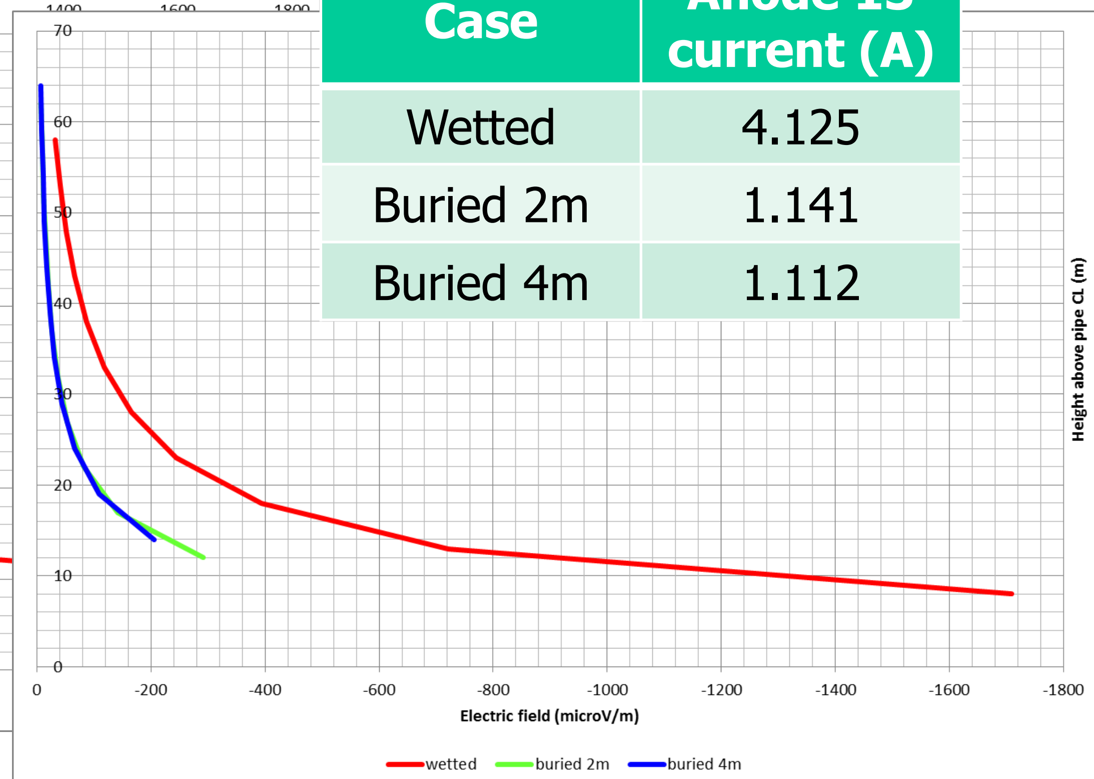
- The following slide shows how the vertical electric field is affected by depth of burial of the pipeline…

Effect of pipeline burial depth on vertical electric field

- Plotting vertical electric field against depth below the sea surface(on the left below) shows significant difference between results for the wetted and the buried pipe, and for the *buried* pipe shows variation with buried depth
- If vertical electric field is plotted against *height above the pipe centre-line* (on the right below), the two curves for the buried pipe are now almost on top of each other. This is rather surprising, but reflects the small difference of anode output for the two buried cases. Further simulation to investigate this effect, and what happens with other buried depths, has not yet been carried out.



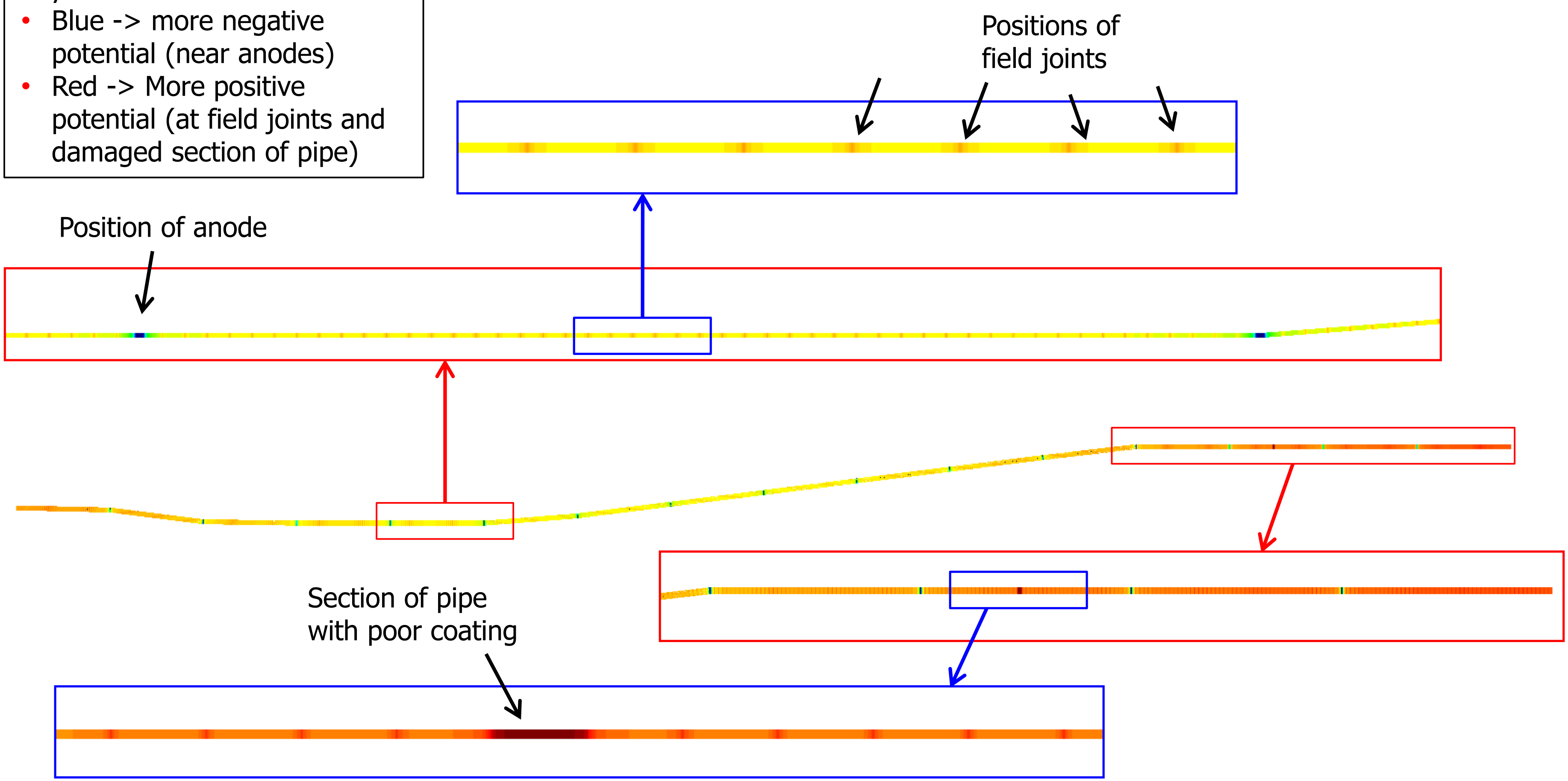
Case	Anode 13 current (A)
Wetted	4.125
Buried 2m	1.141
Buried 4m	1.112



A pipeline with coating damage at field joints and on one section of pipe

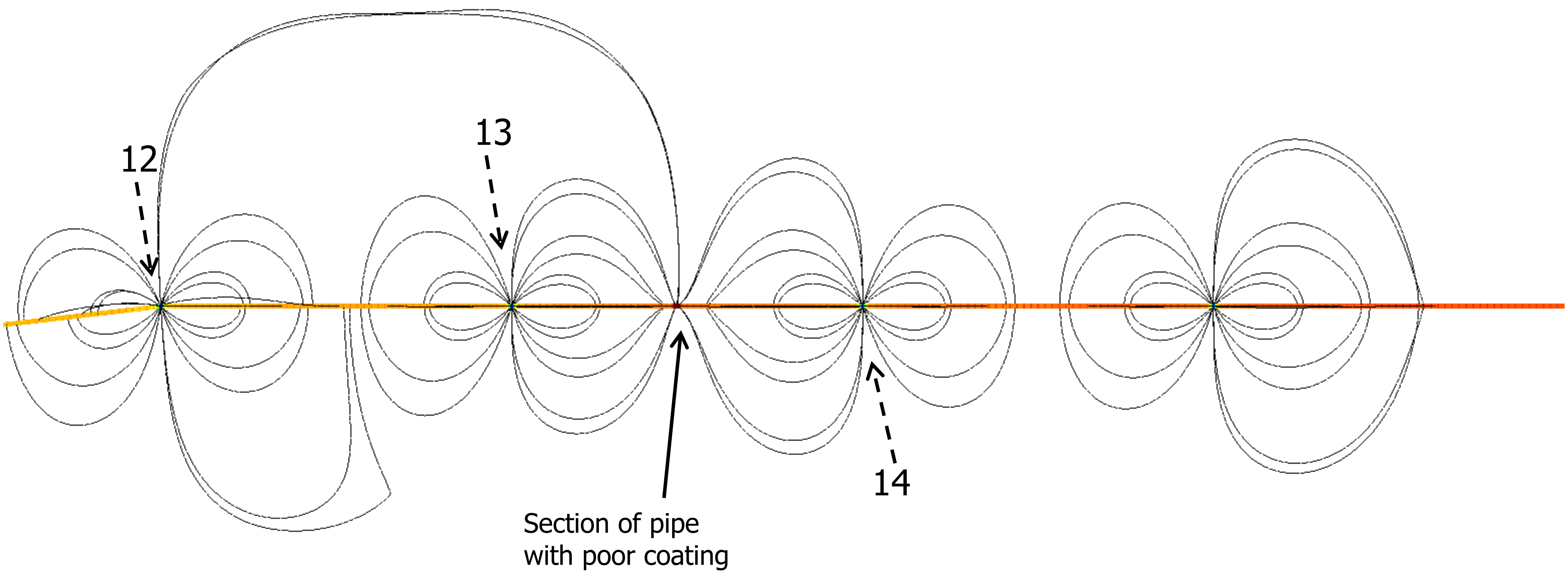
- Here we investigate effects when each field joint has higher coating breakdown, and a single section of pipe also has poor coating
- The image below shows protection potentials, which are more positive at field joints, towards the ends of the pipeline, and at the section of pipe with poor coating

Key:
- Blue -> more negative potential (near anodes)
- Red -> More positive potential (at field joints and damaged section of pipe)



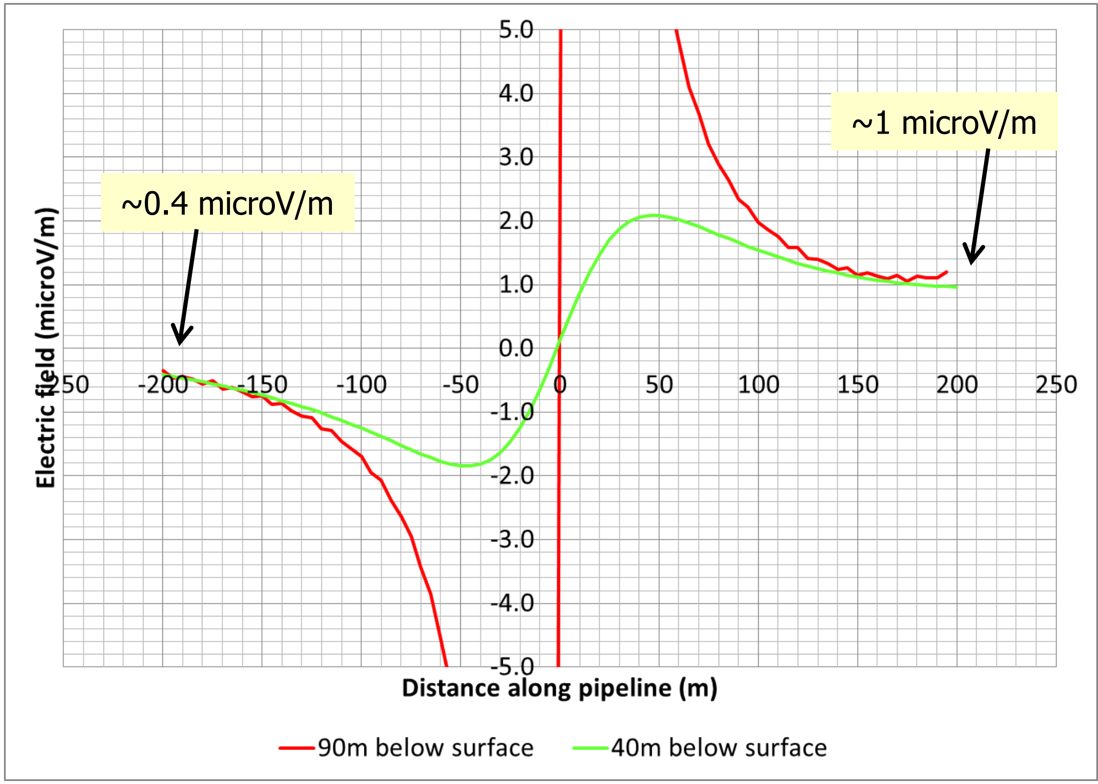
A pipeline with coating damage at field joints and on one section of pipe

- The flowlines (for anodes 12 to 15) clearly highlight the section of pipeline with poor coating as the destination of current from anodes 13 and 14, and in addition from anode 12
- The next slide shows graphs of longitudinal electric field immediately above the pipeline near anode 13…



A pipeline with coating damage at field joints and on one section of pipe

- This graph of longitudinal electric field along lines immediately above the pipeline near anode 13 shows:
  - Bigger electric field to the right, where the magnitude is about 1 microV/m
  - Smaller electric field to the left (further from the section of pipe with poor coating) where the magnitude is about 0.4 microV/m
  - The difference of longitudinal electric field is about the same at 40m and at 90m depth
  - Immediately above the anode the longitudinal electric field is zero
- These features could be used to help locate sections of pipe with poor coating



Future work?

- If three-axis electric field measurements *can* be made with sufficient accuracy during routine pipeline surveys:
  - The measured data could be matched to data similar to that shown on earlier slides
  - The comparison could then be used to determine anode output, which obviously identifies anode mass loss rate.
  - Carried out periodically, changes of estimated anode output can be related to change of coating breakdown factor
- There *may* be no need to accurately position the measurement device above the pipeline
- Clearly simulation results are based on some assumed set of conditions
  - Any additional measurements - such as buried depth or sideways offset of the measurement device from the pipeline – will improve the accuracy of data obtained from the comparison of survey data with simulation

Issues with achieving balanced current distribution for complex well casing configurations and how modelling can facilitate outcomes

Adjustments to return path resistance to control well current

- Imbalance of the amount of current flowing to well casings may be caused by:
  - Casings of different lengths
  - "Shadowing" in which outer casings receive more current than casings in the middle of a group
  - Differences in the resistance between the anodes and the well casing
  - Differences in achieved quality of cementing, or of local conditions

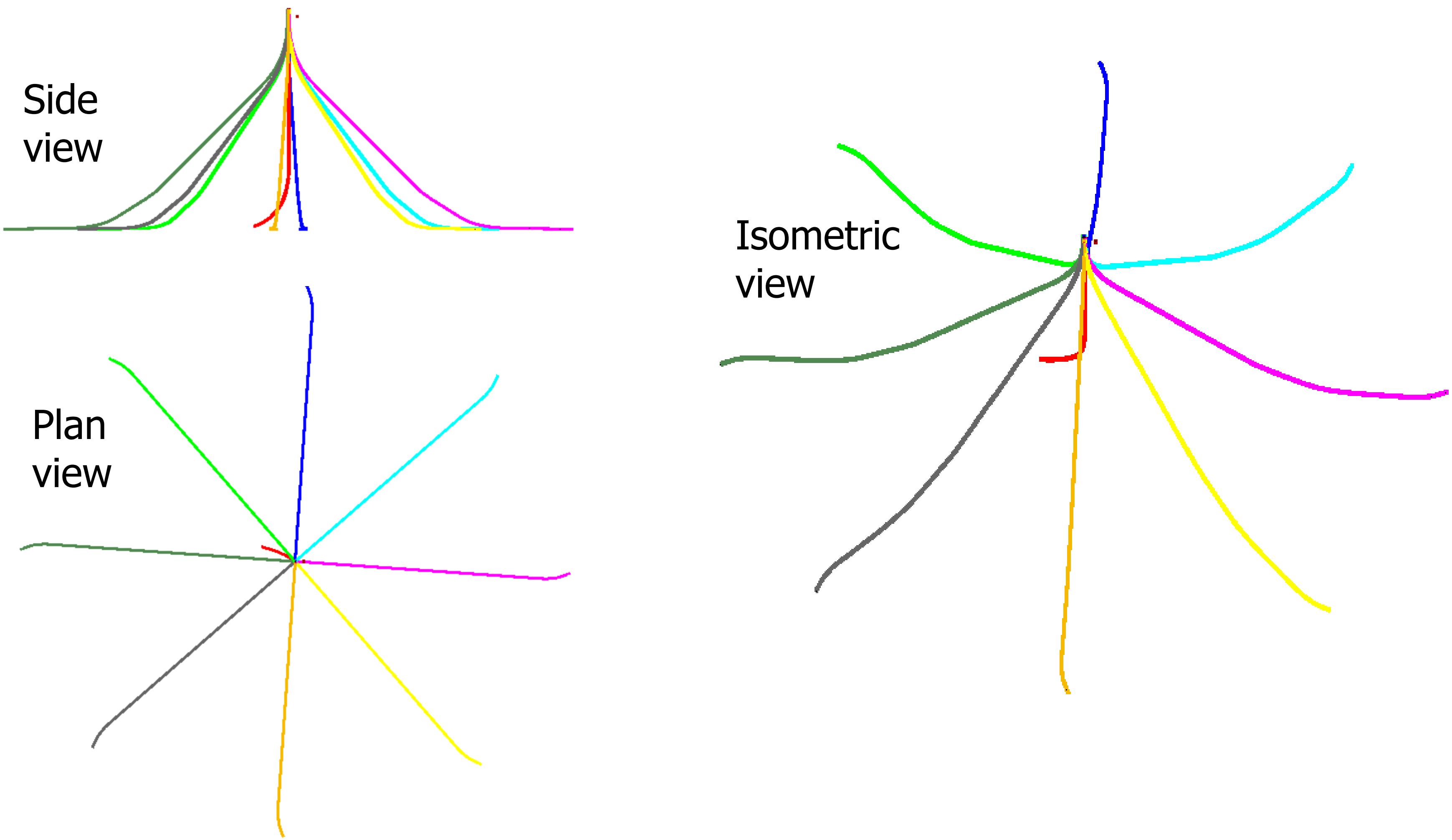
Adjustments to return path resistance to control well current

- Assuming that a target current has been identified for each casing, can return-path resistance be used to achieve the target?

- The following slides show investigation into control of well casing current by adjustment of resistance of return path cabling, for a specific set of parameters (*casing geometry and position, ground resistivity, anode location, connections between well-head and tie-in points, and so on*)

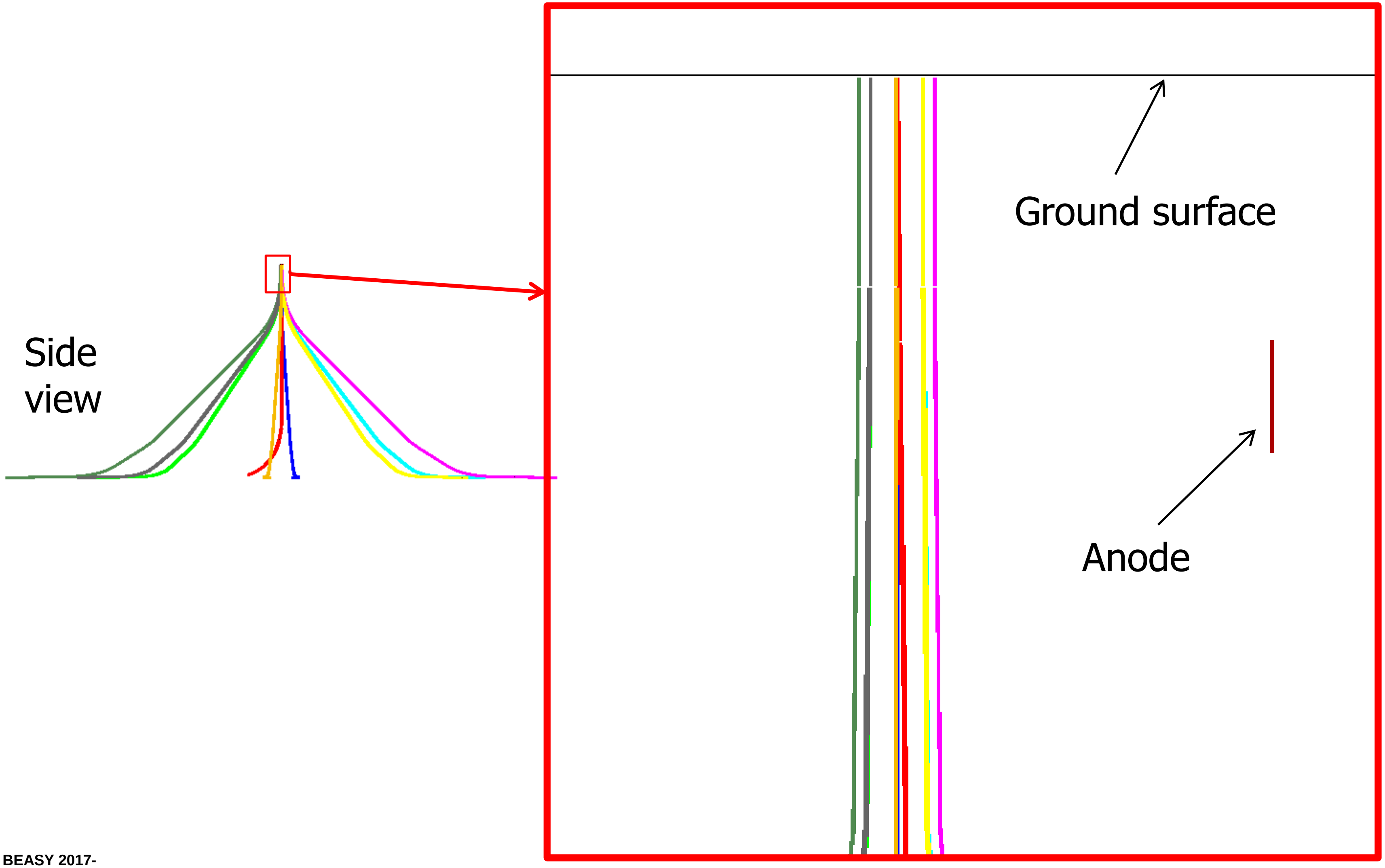
Well casing arrangement

- Assumed geometry includes 9 well casings in a group, with 8 arranged around a central casing



ICCP anode

- There is a deep anode at some distance away horizontally

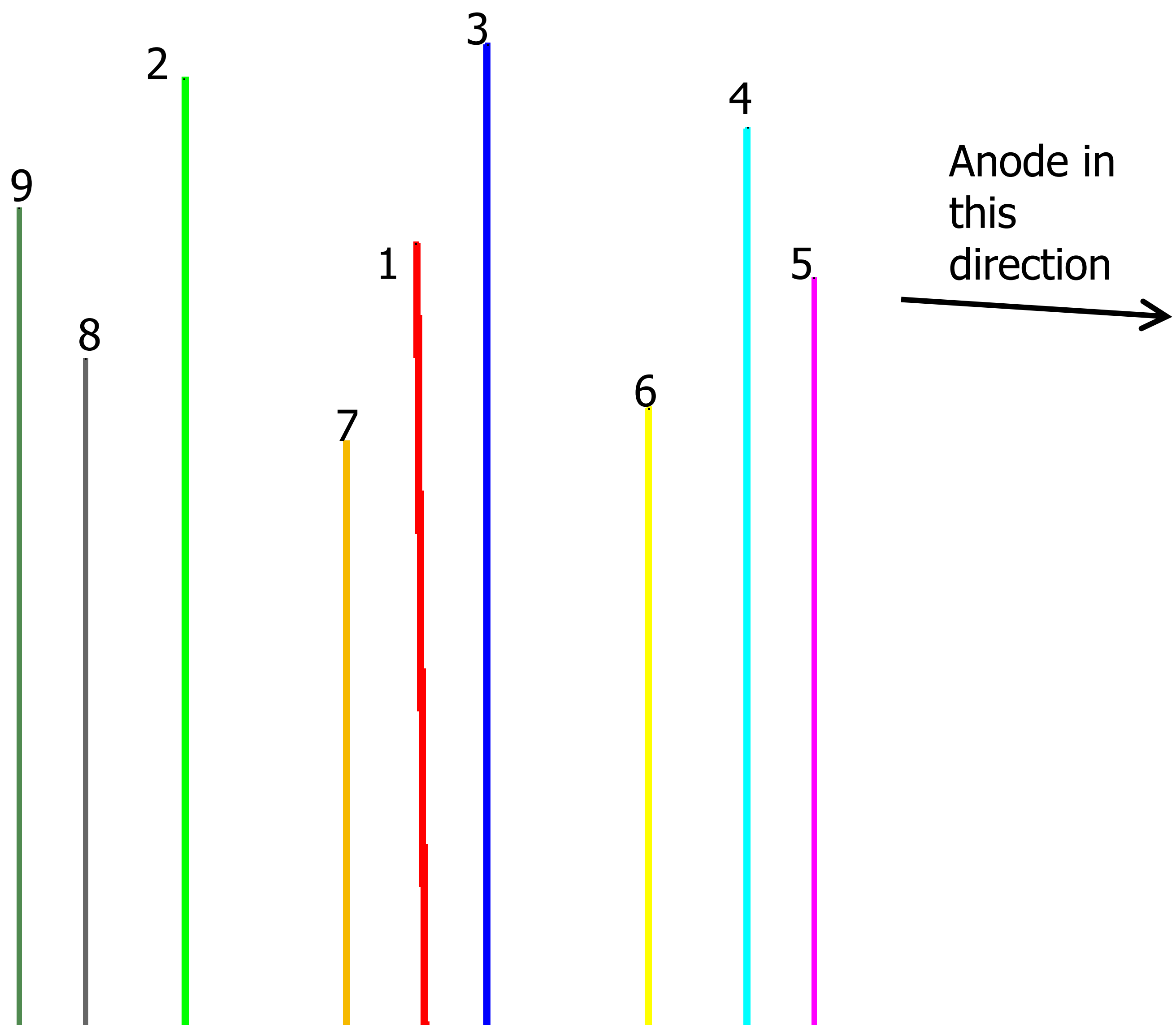


Resistance of pipework

- It is assumed that small diameter pipework connects each well-head to a tie-in point on large diameter pipework, and that:
  - The resistance of the small diameter pipework is the same between each well-head and each tie-in point
  - The large diameter pipework is so massive that it has “zero” internal resistance

Well-head numbering

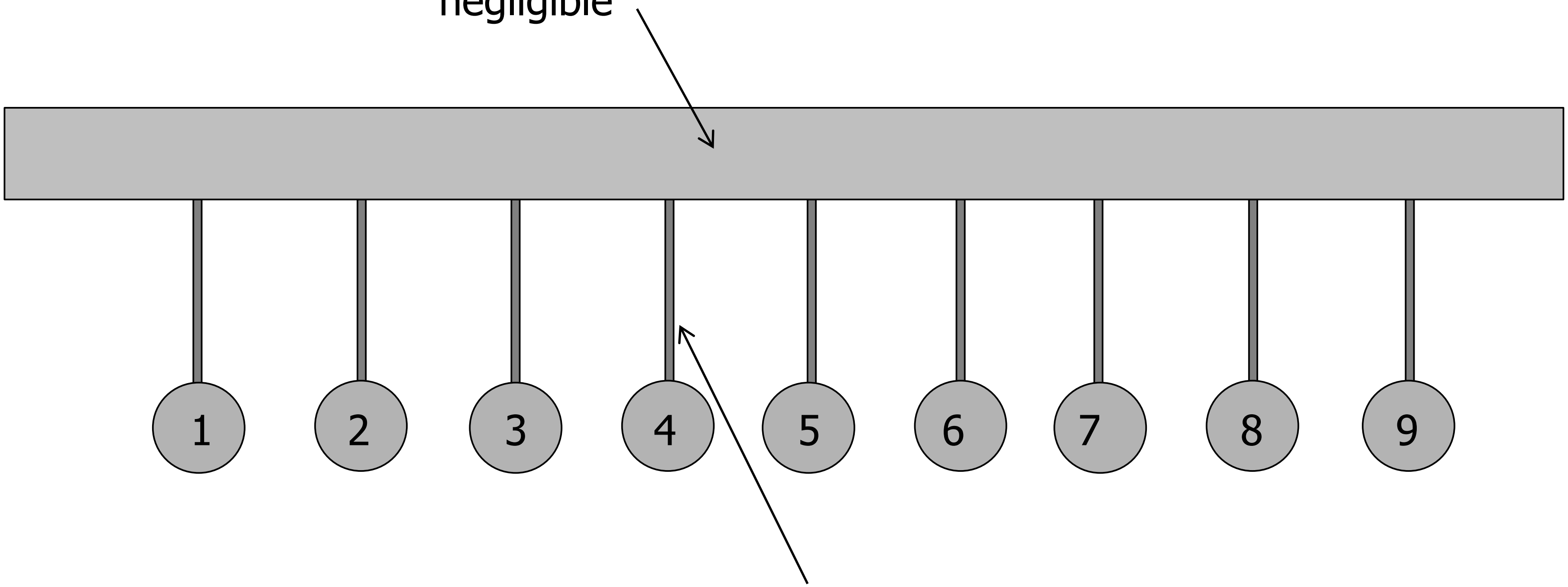
- Well-head 5 is closest to the anode
- Well 1 is surrounded by other wells



Connections from well-head to tie-in points

- Well-head numbers 1 to 9

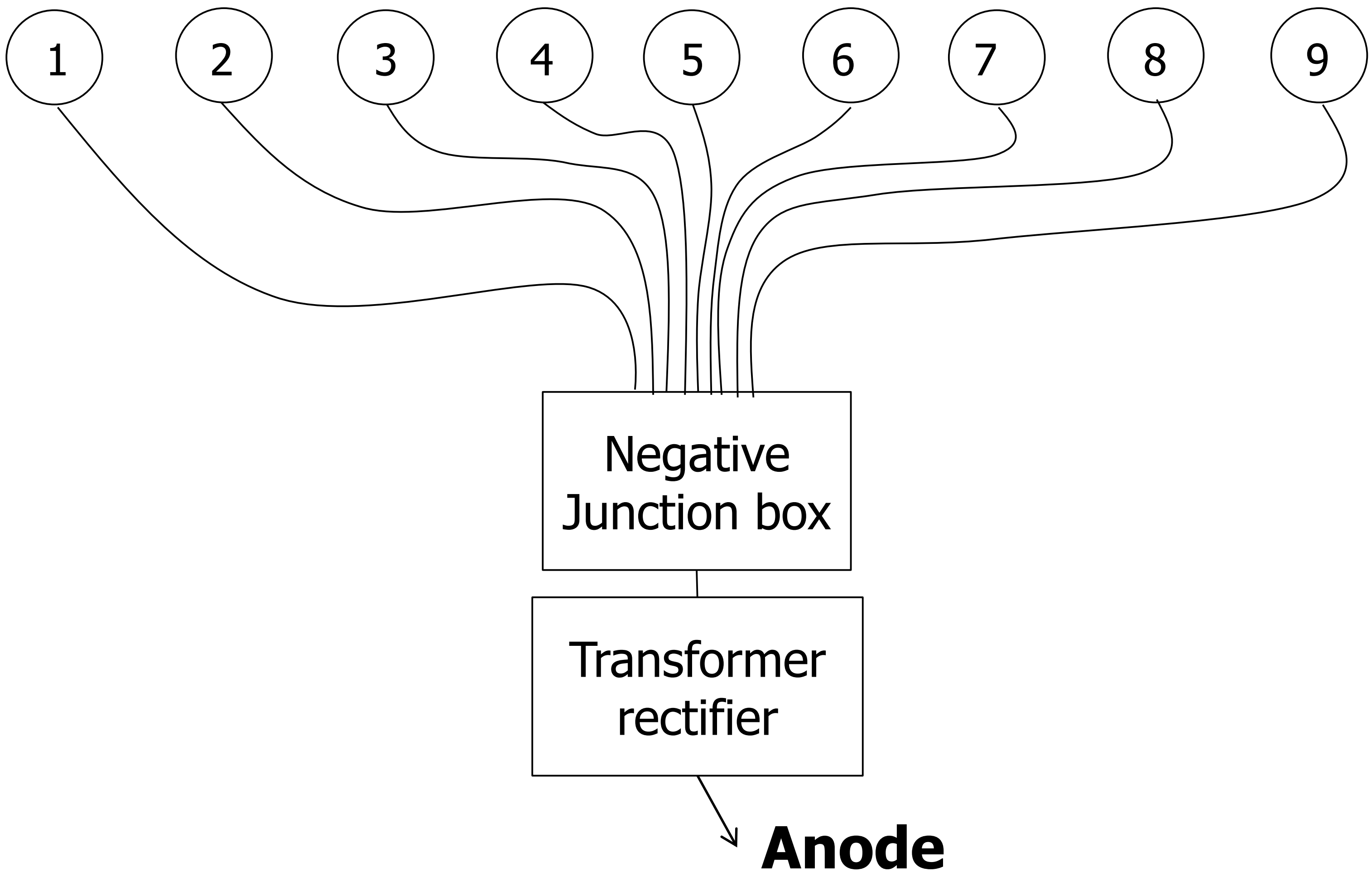
Resistance along large diameter pipework is negligible



Resistance along small diameter pipework is the same between each well-head and its tie-in point

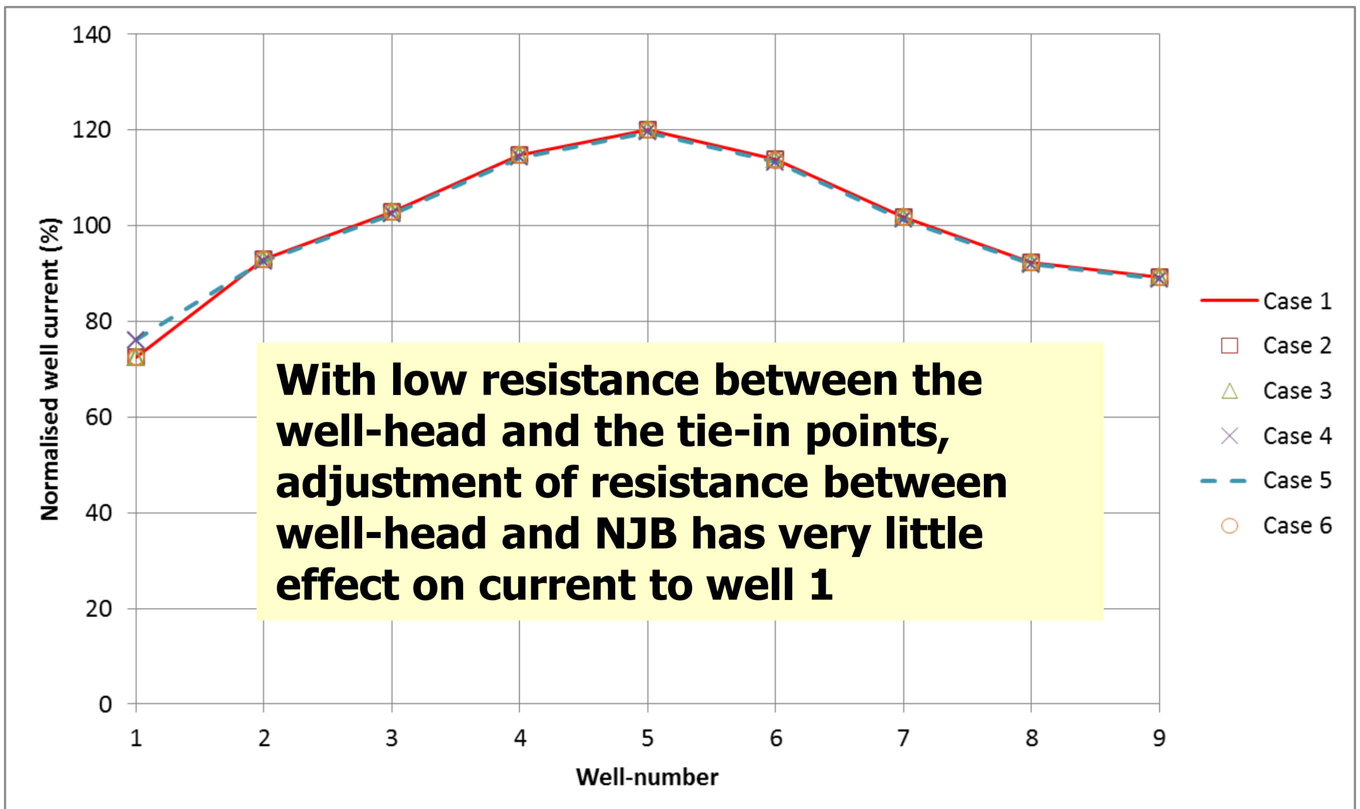
Return-path cabling

- Well-head numbers 1 to 9



Tests with "low" resistance between the well-head and tie-in point

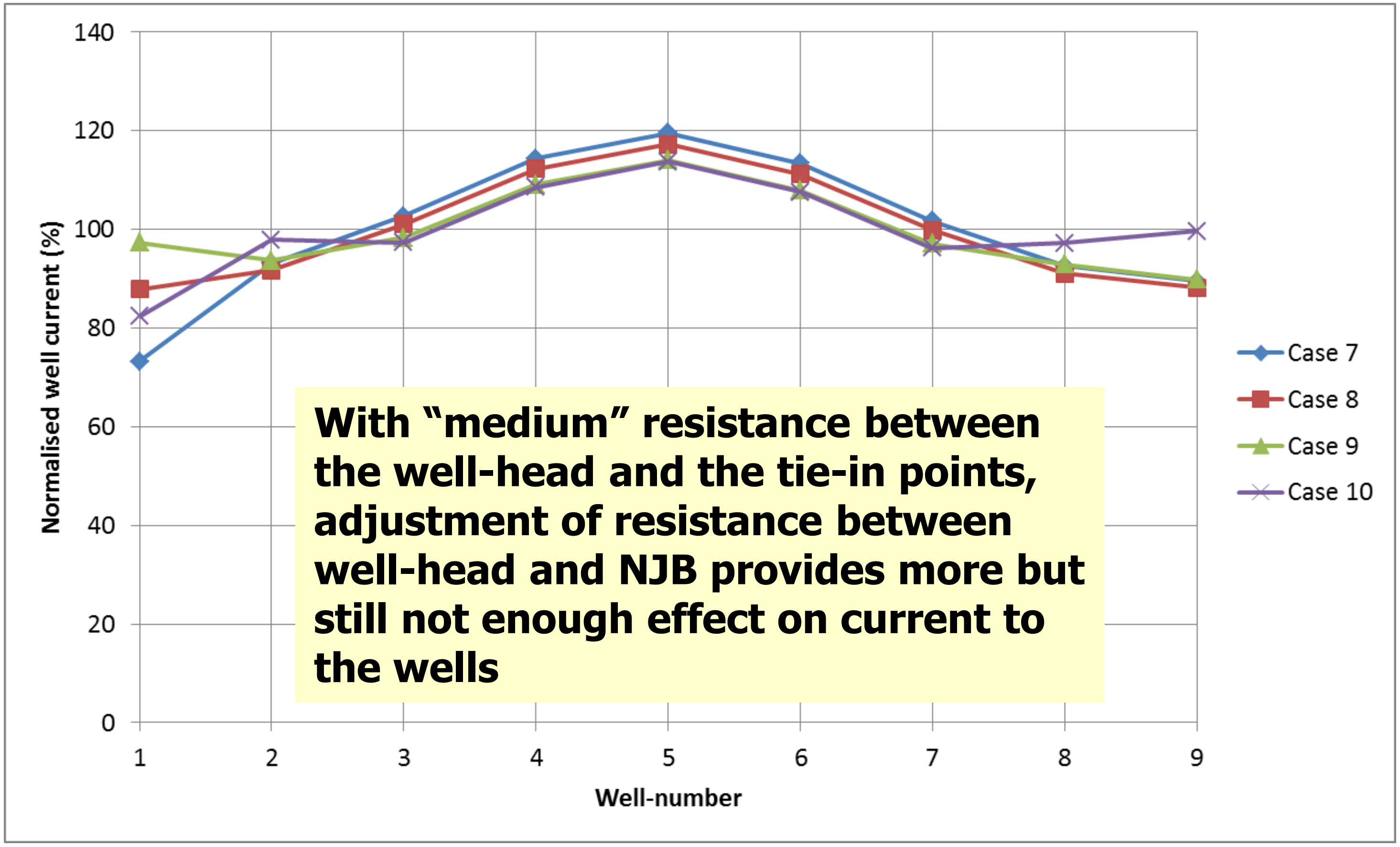
Case	Resistance (Ohms) between each wellhead and its tie-in point	Resistance (Ohms) between the well-head and the negative junction box for well-heads:								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	0	0	0	0	0	0	0	0	0	0
2	0	0	2	2	2	2	2	2	2	2
3	0.0008	0	0	0	0	0	0	0	0	0
4	0.0008	0	2	2	2	2	2	2	2	2
5	0.0008	0	20	20	20	20	20	20	20	20
6	0.0008	20	20	20	20	20	20	20	20	20



With low resistance between the well-head and the tie-in points, adjustment of resistance between well-head and NJB has very little effect on current to well 1

Tests with “medium” resistance between the well-head and tie-in point

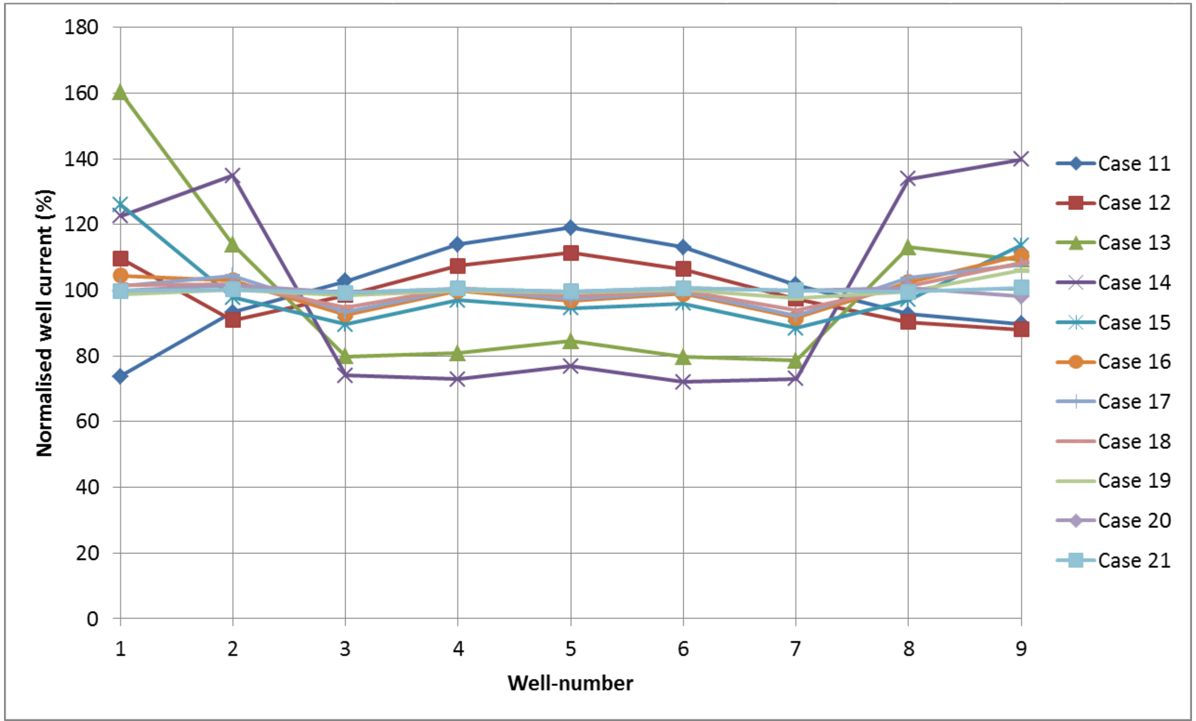
Case	Resistance (Ohms) between each wellhead and its tie-in point	Resistance (Ohms) between the well-head and the negative junction box for well-heads:								
		1	2	3	4	5	6	7	8	9
7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8	0.01	0.01	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
9	0.01	0.01	0.1	0.5	1	1	1	0.5	0.1	0.1
10	0.01	0.01	0.02	0.5	10	10	10	0.5	0.02	0.01



With “medium” resistance between the well-head and the tie-in points, adjustment of resistance between well-head and NJB provides more but still not enough effect on current to the wells

Tests with "high" resistance between the well-head and tie-in point

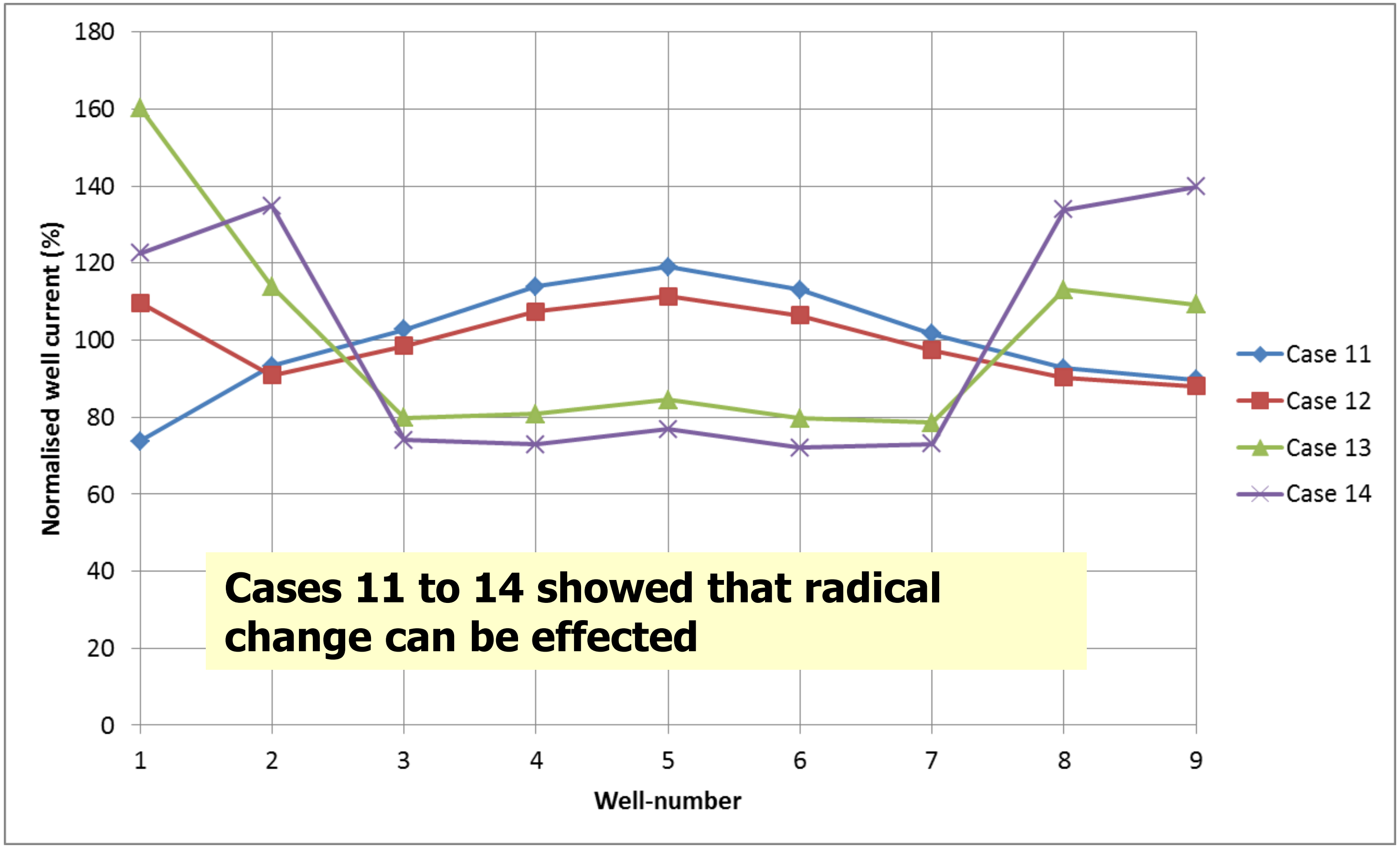
Case	Resistance (Ohms) between each wellhead and its tie-in point	Resistance (Ohms) between the well-head and the negative junction box for well-heads:								
		1	2	3	4	5	6	7	8	9
11	0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12	0.1	0.01	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
13	0.1	0.01	0.1	0.5	1	1	1	0.5	0.1	0.1
14	0.1	0.01	0.02	0.5	10	10	10	0.5	0.02	0.01
15	0.1	0.01	0.1	0.2	0.22	0.3	0.22	0.2	0.1	0.05
16	0.1	0.05	0.1	0.2	0.22	0.3	0.22	0.2	0.1	0.07
17	0.1	0.06	0.1	0.2	0.22	0.3	0.22	0.2	0.1	0.08
18	0.1	0.06	0.11	0.19	0.22	0.29	0.22	0.19	0.11	0.08
19	0.1	0.07	0.12	0.17	0.23	0.28	0.22	0.17	0.12	0.09
20	0.1	0.07	0.12	0.17	0.23	0.28	0.22	0.16	0.12	0.12
21	0.1	0.07	0.125	0.17	0.23	0.28	0.22	0.16	0.125	0.11



With "high" resistance between the well-head and the tie-in points, adjustment of resistance between well-heads and NJB allows complete control of current to the wells

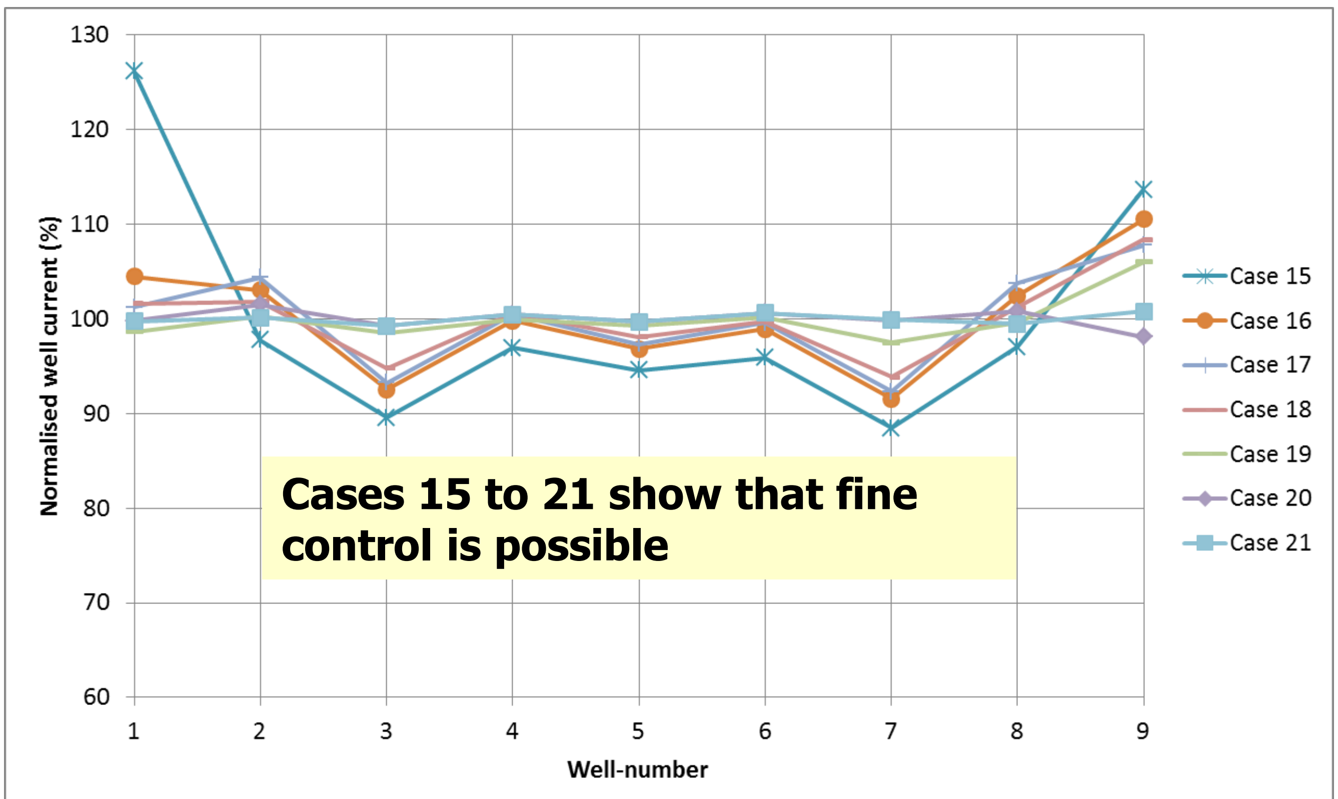
Tests with “high” resistance between the well-head and tie-in point

Case	Resistance (Ohms) between each wellhead and its tie-in point	Resistance (Ohms) between the well-head and the negative junction box for well-heads:								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
11	0.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
12	0.1	0.01	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
13	0.1	0.01	0.1	0.5	1	1	1	0.5	0.1	0.1
14	0.1	0.01	0.02	0.5	10	10	10	0.5	0.02	0.01



Tests with "high" resistance between the well-head and tie-in point

Case	Resistance (Ohms) between each wellhead and its tie-in point	Resistance (Ohms) between the well-head and the negative junction box for well-heads:								
		1	2	3	4	5	6	7	8	9
15	0.1	0.01	0.1	0.2	0.22	0.3	0.22	0.2	0.1	0.05
16	0.1	0.05	0.1	0.2	0.22	0.3	0.22	0.2	0.1	0.07
17	0.1	0.06	0.1	0.2	0.22	0.3	0.22	0.2	0.1	0.08
18	0.1	0.06	0.11	0.19	0.22	0.29	0.22	0.19	0.11	0.08
19	0.1	0.07	0.12	0.17	0.23	0.28	0.22	0.17	0.12	0.09
20	0.1	0.07	0.12	0.17	0.23	0.28	0.22	0.16	0.12	0.12
21	0.1	0.07	0.125	0.17	0.23	0.28	0.22	0.16	0.125	0.11



Conclusions

- The ability to use resistance of return-path cabling to control the amount of current flowing to individual wells is dependent in the first place on ***not*** having a very low resistance connection between well-heads through pipework
- It is likely that the effectiveness of such measures will vary with the detail of such parameters as:
  - Number, layout and shape of well casings
  - Ground resistivity
  - Corrosivity of the ground
  - Competence of cementing
- Such measures will cause development of potential differences between well-heads