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Reply by the authors to the discussion by Cho and Kim

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We appreciate the discussion by Cho and Kim. In the discussion, two points are addressed. One is that the secondary electric field cannot be greater than the primary field and the other is the accuracy of numerical results.

Primary and secondary fields

For most geological conditions, we agree that the secondary electric field cannot be greater than the primary electric field. In our paper, we tried to explain that in a certain

Table 1. Investigation of negative apparent resistivity with several modelling algorithms.
FDM, finite difference method; FEM, finite-element modelling.

Depth	RES3DMOD (FDM)	RES3DMOD (FEM)	DCIP3D (FDM)	Code A (FEM)
3 m	Negative	Negative	Negative	Negative
4 m	–	Negative	Negative	Negative
5 m	–	Negative	Negative	–

Table 2. Investigation of reciprocity theorem with several modelling algorithms.
FDM, finite difference method; FEM, finite-element modelling.

	RES3DMOD (FDM)	RES3DMOD (FEM)	DCIP3D (FDM)	Code A (FEM)
With the reference of the centre of the U conductor	Symmetric	Symmetric	Asymmetric	Asymmetric

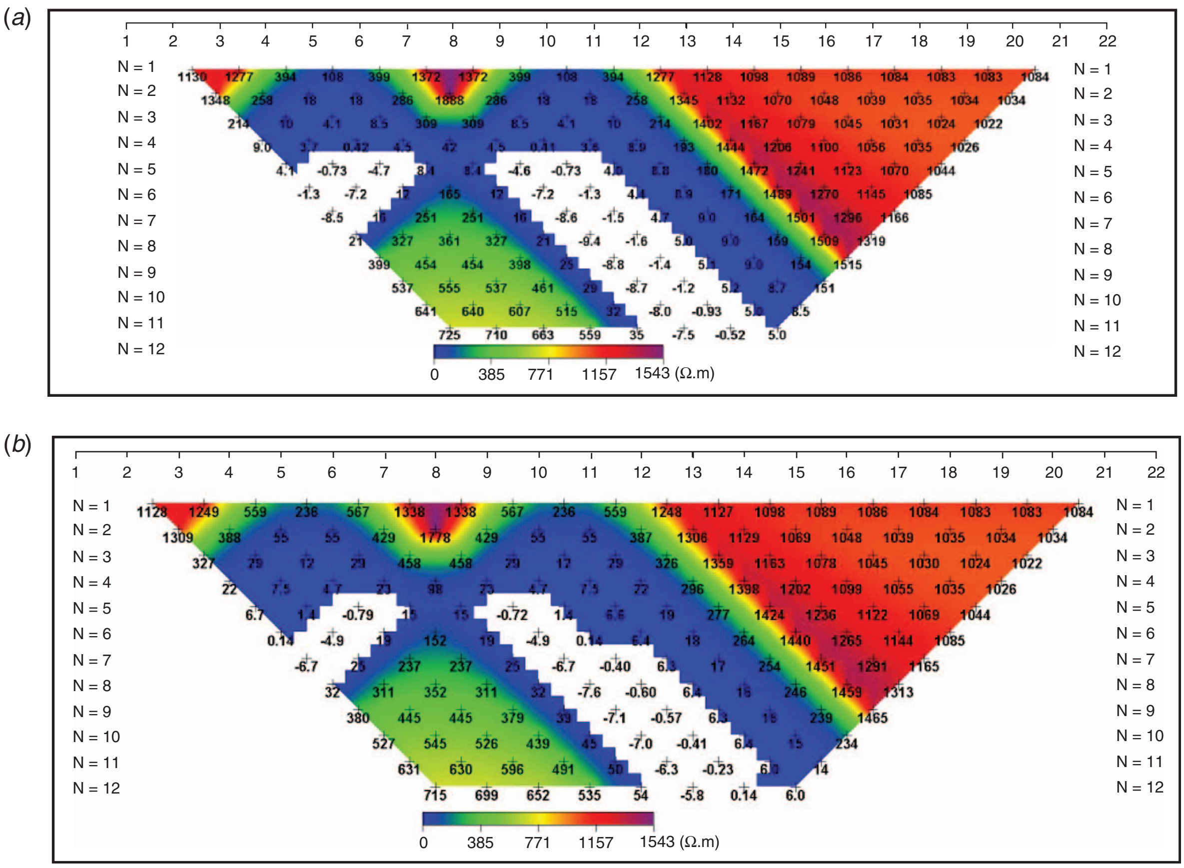

Fig. 1. Pseudosections obtained by RES3DMOD (finite difference method). The U-shaped conductor is buried at the depths of (*a*) 3 m, (*b*) 4 m, and (*c*) 5 m.

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(*c*)

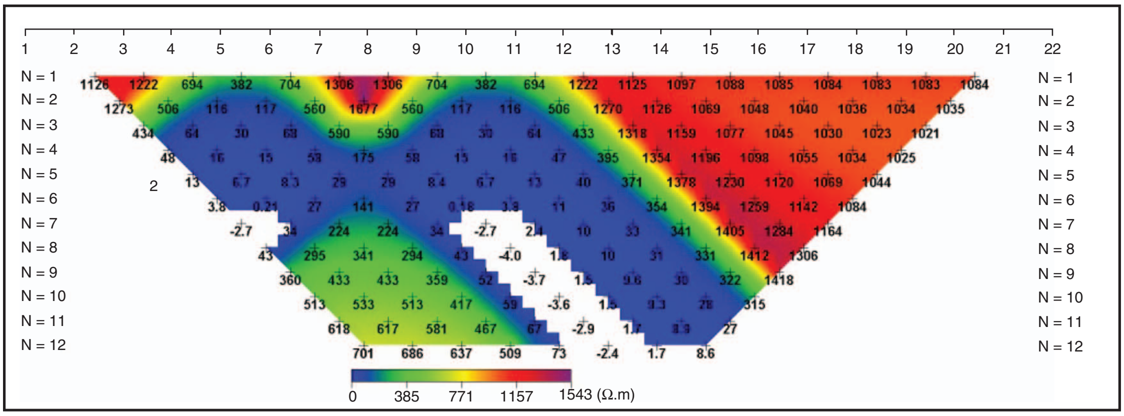

Fig. 1. (*continued*)

(*a*)

(*b*)

(*c*)

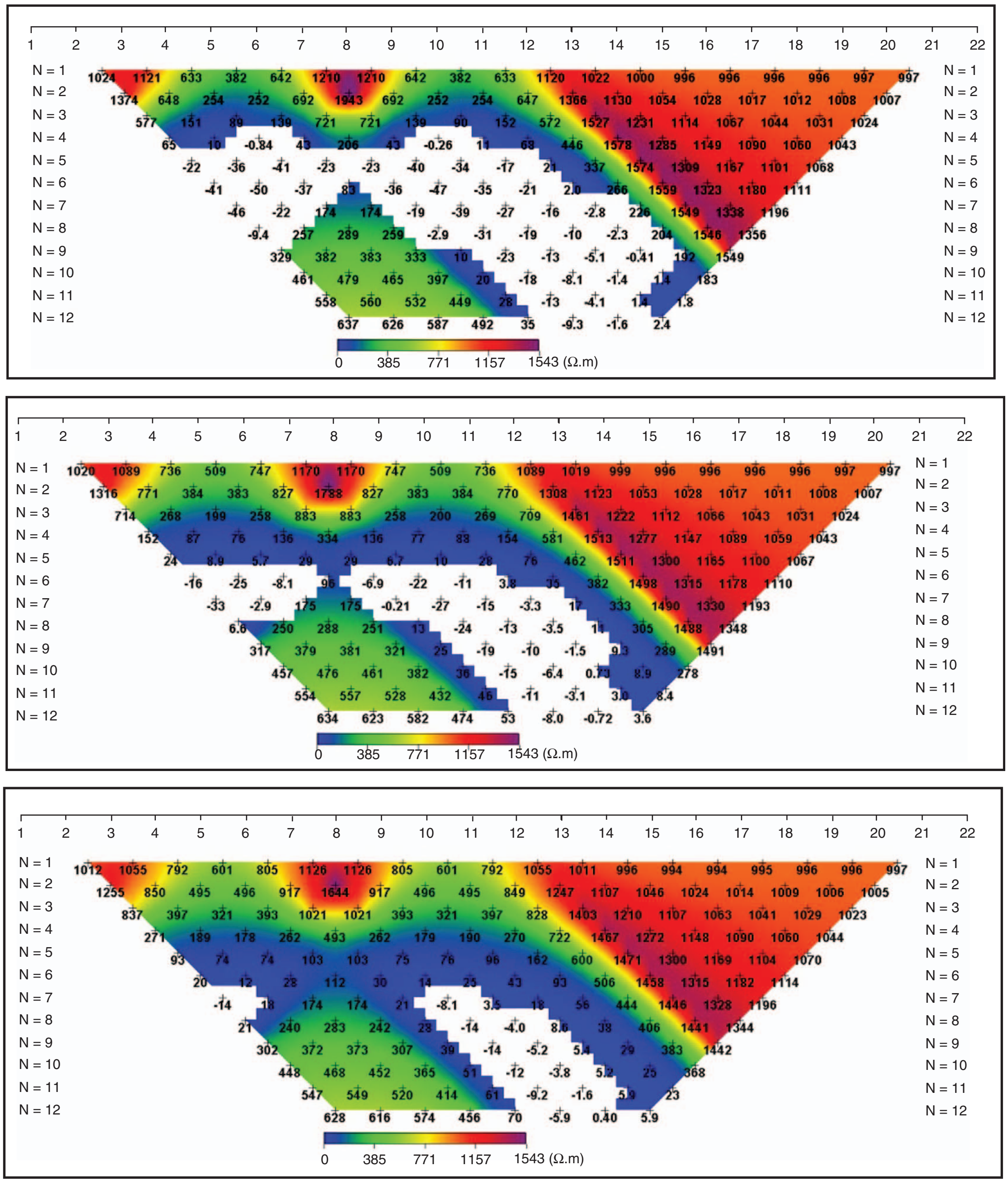

Fig. 2. Pseudosections obtained by RES3DMOD (finite-element modelling). The U-shaped conductor is buried at the depths of (*a*) 3 m, (*b*) 4 m, and (*c*) 5 m.

geological model with a conductor, the potential could increase with distance from current electrodes, which might lead to negative apparent resistivity when we adopt the dipole-dipole configuration. We thought that such a geological model could show similar surface electrical potential distributions to those expected in the mise-a-la masse method, although electrodes are not directly planted into a conductor but near a conductor. Such a model is not common, but it can exist in reality.

When we generated 3D equipotential distributions for the U-shaped conductor model (although we do not provide examples in this reply, we may show them in another paper in the near future), we were able to note that the equipotential map reflects the existence of an effective source. That is, if current electrodes were located around the one branch of the U-shaped conductor, with a resistivity contrast of 1 : 10 000 between the conductor and the surrounding medium, the other branch acted as an effective source.

Let us examine electric potential distribution when the current electrodes are located around the left branch of the U conductor. The electric potential drops more slowly within the U-shaped conductor than in the surrounding resistive media, which may lead to a high potential gradient between the U-shaped conductor and the surrounding media. As a result, the electric potential recorded at the surface may not decrease monotonously with distance from the current electrodes as it does in homogeneous cases, and the potential may show little variation with distance above the centre of the U-shaped conductor. In that case, we may obtain apparent resistivity values close to zero, or small negative values due to random electrical noise, in a field experiment. The electric potential between the centre and the right branch of the U-shaped conductor may increase with the distance, giving rise to

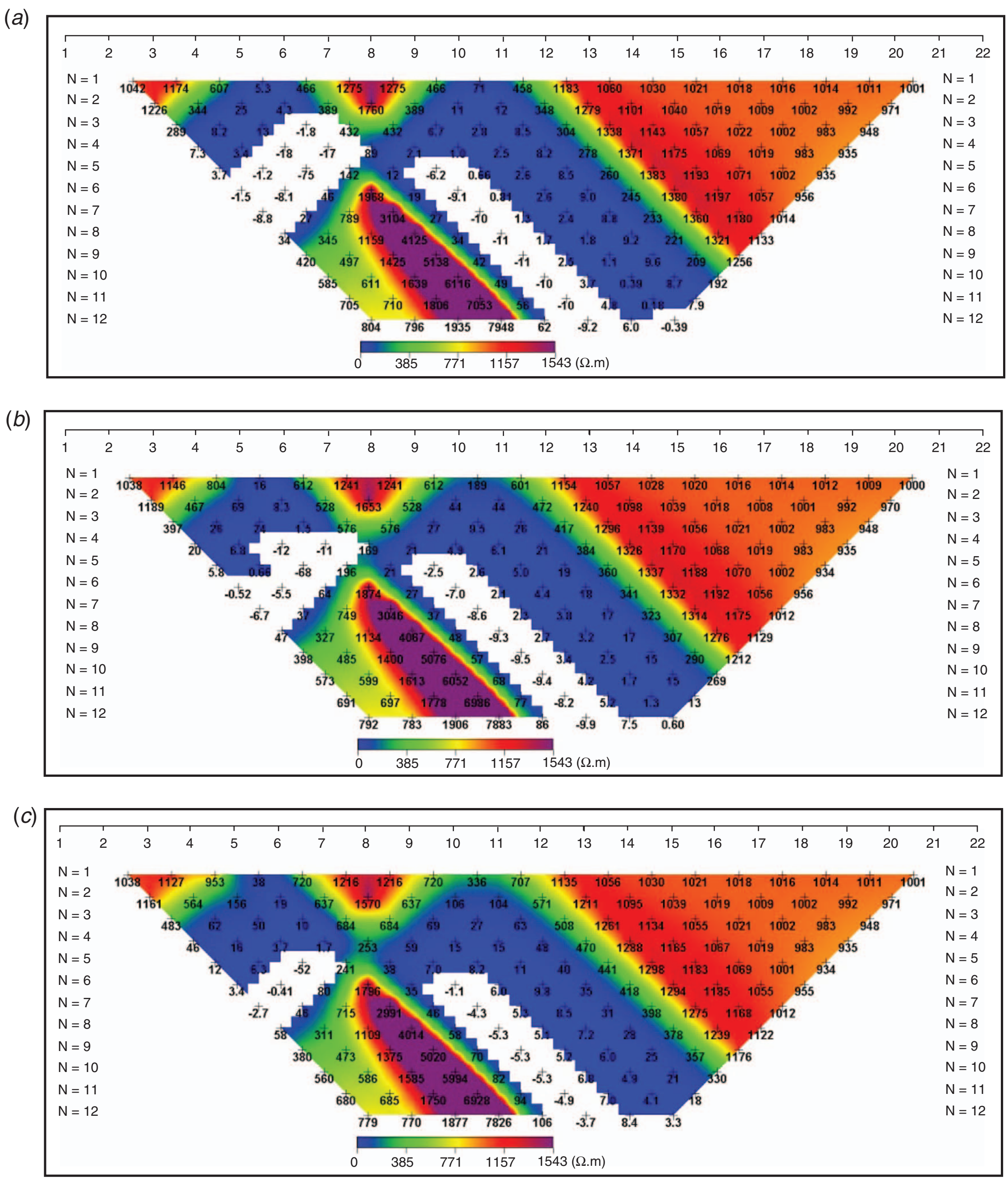

Fig. 3. Pseudosections obtained by DCIP3D (finite difference method). The U-shaped conductor is buried at the depths of (*a*) 3 m, (*b*) 4 m, and (*c*) 5 m.

negative apparent resistivity. Beyond the right branch of the U-shaped conductor, the electric potential decreases with the distance, which results in abnormally high positive apparent resistivity values due to high potential differences and geometrical factors. One of the extreme examples is a perfect conductor insulated except at each end.

Numerical errors

We agree that the accuracy of the numerical modelling code is very important. However, it was a secondary issue in our paper, because we focused on addressing how the negative apparent resistivity occurs in reality rather than analysing the accuracy of the modelling code. In addition, the modelling code was demonstrated for general cases, and our convergence tests showed that the modelling code yielded consistent results as the number of cells between electrodes increases. We should admit that some numerical errors are included in our results, and our model may not be the optimal case. The depth of the U-shaped conductor should have been shallower. In the beginning, we dealt with a model where the top of the conductor is located at the depth of 1 m, but as we carried out convergence tests the model was accidently changed so that the conductor was buried at the depth of 5 m.

Applying several 3D modelling codes (which are well known and have widely been used) to the U-shaped conductor model for this reply to the discussion, we found that some of them yielded negative apparent resistivity for the original model provided in our paper, but the others did not (Table 1). In Table 1, 'Code A' indicates a 3D finite-element modelling (FEM) algorithm provided by a Japanese geophysicist. Moreover, some numerical codes gave numerical results symmetrical with respect to the central axis (which indicates that the reciprocity theorem is satisfied), but the others did not (Table 2). In Figures 1–3, we display numerical results obtained by RES3DMOD (www.geoelectrical.com; verified 22 January 2010), and DCIP3D (developed at the University of British Columbia). From Figures 1–3, we observe that all the modelling codes used in our experiments showed negative apparent resistivity for the U-shaped conductor when the top of the conductor is located at the depths shallower than or equal to 3 m. From these results, we feel that we need a more accurate 3D modelling algorithm that can deal with such high resistivity-contrast models. Since our paper is a first attempt to explain the negative apparent resistivity that exploration geophysicists have often observed in field surveys, our study may not be perfect. To correctly address the negative apparent resistivity, further study is needed.

The discussion of our paper pointed out weaknesses of our study that we had overlooked. We really appreciate the efforts of Cho and Kim. We will try to compensate for those weaknesses in our future studies.

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