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Numerical simulation of compound media coupling mechanism of deep mining overburden strata

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Abstract: Aiming at the regularity of deep mining strata movement, through the application of plate theory and discrete medium theory in establishing the coupling model of the deep mining strata composite medium, the continuum media and the non-continuum media were coupled into the compound media giant system, and the stress of compound layer and strain coupling relationship were established. The accuracy of forecasting surface subsidence in deep mining conditions was improved. The deep mining was simulated through 3-D numerical value by the FLAC3D finite difference software, and the coupling relationship and coupling layer in the strata composite layer were analyzed. The results show that, under the deep mining condition, the coupling zone is in the position of coal seam roof with the thickness of 15−20 times, on which, the stress−strain has much difference on the coupling zone. Considering interlayer effect of coupling zone can improve the prediction precision of surface subsidence.
Key words: deep mining; numerical simulation; coupling mechanism

1 Introduction

The exploitation of mineral resources is a very important part in the survival and development of human society. It is predicted that 95% of the energy and 85% of raw materials will still depend on mineral resources in future. The coal mining will gradually extend into the deeper region. And the mining intensity will be strengthened accompanying the progress of mining technology. In the process of intensive deep mining, many growing problems appears, such as mine pressure, strata movement and frequency mining subsidence. Meanwhile, the regularity and deformation mechanism of overlying rock mass movement are rather complicated. Therefore, researching these problems can be helpful to furtherly find the stratum subsidence process, reduce the possibility of occurring mining subsidence disasters, recover the strata movement and control the subsidence areas, which has extremely important value for solving the problem of “three-times” mining, reducing the damage of buildings in villages and infrastructure as well as protecting arable land and the environment.

Chinese scholars have done a lot of researches on this field. For example, the simulation experiment applied with similar materials was done to study the regular pattern of mining subsidence [1−3] to field observe and theoretically study the mining subsidence [4−7] and to exploit mines with 3-D simulation and so on [8−11]. However, there are few researches on deep overlying strata of coupling, even exist, few consider interlayer coupling has an effect on surface subsidence.

Based on the finite difference technology FLAC3D to simulate deep mining, the mechanism of the coupling and mining subsidence rule was studied, and the theoretical help to mine safety production of deep mining conditions was provided.

2 Model of compound media coupling

2.1 Movement process of layered media upper strata

According to the upper strata (bending plate) mechanics model and the right hand spiral rules, z direction should be negative pressure. When pressure p is in z direction, if the deflection is $W(x, y, z)$, then the equilibrium differential equation is

$$D\nabla^4 W = -p(x, y) \tag{1}$$

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where $\nabla^4=\frac{\partial^4}{\partial x^2}+2\frac{\partial^4}{\partial x^2\partial y^2}+\frac{\partial^4}{\partial y^2}$ is biharmonic operator of xoy plane; $D=Eh^3/[12(1-\mu^2)]$ is flexural rigidity; h is thickness; E is elastic modulus; μ is Poisson ratio.

According to Refs. [10−11], in order to research the problem of convenience, take small pieces of rock j layer, j+1 layer and j+2 layer as the research object, the method force on j+1 layer board is P_{j+1}:

$$P_{j+1}=\sigma_b-\sigma_i \tag{2}$$

where σ_b and σ_i is vertical forces of j+1 bottom and top layer board. Then,

$$P_{j+1}=2E_{j+1}\left[\frac{E_j}{k_j}(W_{j+2}-W_{j+1}+W_j)+\left(\frac{E_{j+2}}{k_{j+1}}-\frac{E_j}{k_j}\right)(W_{j+2}-W_{j+1})\right] \tag{3}$$

$$D_{j+1}\nabla^4W(x,y,z)+P_{j+1}(x,y)=0 \tag{4}$$

$$\lambda^2\nabla^4W+\frac{\partial^2W}{\partial Z^2}=0 \tag{5}$$

where $\lambda^2=\frac{h^2}{12(1-\mu^2)}$.

2.2 Movement process of discrete medium under strata

The discrete by cutting or diving in the cracks of block as the starting point, the blocks interaction between the surface and angle, the angle can allow a large displacement, in some cases, such as landslide or roof caving, even from sliding rock matrix and free falling.

2.3 Coupling of layered media and discrete medium

Coupling of the layered media and discrete medium is two kinds of medium area (Fig.1), which should satisfy the coupling of continuity conditions of displacements. The coupling of layered media for regional vertical displacement is

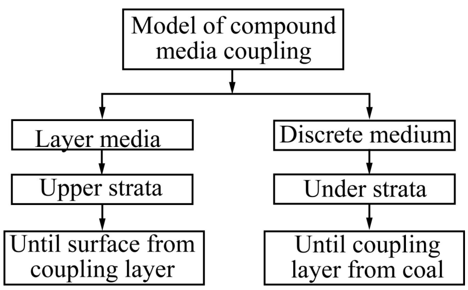

Fig. 1 Flowchart of coupling model

$$W_y(x,y)=\frac{M}{4\pi\lambda H}\cdot\iint_B\exp\left[-\pi\frac{(x-x_0)^2+(y-y_0)^2}{4\lambda H}\right]\mathrm{d}x_0\mathrm{d}y_0 \tag{6}$$

The vertical displacement of discrete medium in the interaction regions is

$$W_y(x,y)=W_y(t_0)+\frac{F_y}{m}\Delta t \tag{7}$$

where F_y is the force of y direction; m is reeks quality; M is coal thickness; t_0 is starting computing time. $t_1=t_0+\Delta t$ (time step), two kinds of medium in coupling area $W_y(x, y)$ should with $W_y(t_0)$ approximate the same.

According to the experiment, discrete element simulation calculation and the actual observation, the upper boundary height under a rock is about 20 times for mining thick, rocks in the region have no caving phenomenon.

3 Numerical simulation of deep mining

3.1 Numerical model establishment and parameter selection

1) Model establishment

Because rock (body) has high compressive strength and very low tensile strength and its stress−strain relations also presents complex nonlinear characteristics, in the numerical analysis of rock mechanics elastoplastics, the physical model are quite flexible, the model constitutive relation, whether correct or not, directly affects the meaning of calculation results. The rock-mass failure is generally understood as plastic damage, the yield rock is approximately regarded as elastomer, it shows the plastic quality, so the ideal elastic-plastic constitutive model was elected as coal rock constitutive relation, considering the low tensile properties of the rock, the Coulomb Mohr-plastic constitutive model and Mohr-Coulomb yield criterion were put to use.

The model length (x direction) 2 000 m, width (the y direction) 1500 m, height (z direction) 1000 m was established. There were 12 layers in this model, from top to bottom is 1−12, there were 109200 units and 120907 nodes. Coal seam was the 11th floor, set surface elevation as 0, then coal seam lied in −836− −836 m, 6 m thick. In order to facilitate balanced compute between its accuracy and time, the seam roof unit was encrypted as shown in Fig. 2.

2) Parameter determination

The physical mechanical parameters of rock obtained through indoor rock mechanics experiment, as seen in Table 1.

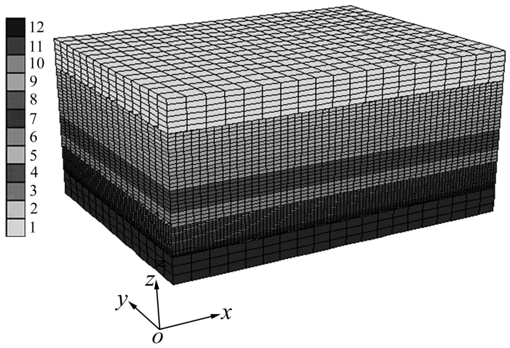

Fig. 2 Mesh dissection schemes of numerical simulation

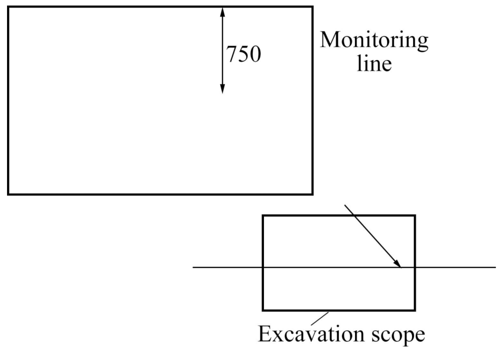

Fig. 3 Monitoring band and excavation space range

3.2 Initial condition and boundary condition

1) Initial condition

In the simulation process, the real unit excavation space will become empty units, with the goaf area expanding unceasingly, caving rock of mined-out area is gradually compacted from loose rock. So, in simulation compaction process, the mechanical parameters of rock falls in the goaf area was given in terms of loose rickles. The range of excavation space was y (400−1100 m), x (500−1500 m), z (−836−−830 m), in simulation process, the stimulation, which the step distance was pushed up to 200 m each time, was adopted, and can be divided into five steps.

In order to get the regular patter of surface subsidence and the overlying rock coupling, four paralleled subsidence monitoring zone were arranged to the z direction, in the profile of surface with y of −750 m, −380 m, −680 m and −830 m, on each monitoring zone equably arranged and put 21 points. Subsidence monitoring zone and excavation space range are shown in Fig. 3.

2) Boundary conditions

Boundary condition is the external factor that controls the joint action and way of geological body stress. The numerical simulation sketched the following boundary conditions: 1) Both the front-back side and left-right side of the model are imposed constraints of the horizontal direction, namely its boundary nodes for zero horizontal displacement; 2) Model on the bottom x, y, z direction fixed constraint, namely the bottom boundary node displacement is zero. 3) Model top is free boundary.

The rock is different form the actual rock mass, there is a great difference between indexes of rock mass physical mechanics and the indexes of rock physical mechanics from indoor test. Therefore, before the excavation, the models should reach to be balanced by the action of gravity, the calculating stress results should be the initial stress of later excavation.

3.3 Numerical model simulated results analysis

1) z direction deformation of four monitoring zone in five excavation step by the simulation is obtained in Fig. 4.

From Fig. 4, in the mining process, with the mining face forward, the mining length increases, the sinking

Table 1 Physical mechanical parameters of stone

Number	Bulk modulus/GPa	Cohesion modulus/MPa	Friction angle/(°)	Shear strength/GPa	Tensile strength/MPa	Density/(kg·m^{-3})
1	0.083	0.125	24	0.011	0.30	1 970
2	0.20	0.126	15	0.031	0.12	1 970
3	0.22	0.039	25	0.049	0.40	1 870
4	0.46	0.155	30	0.083	1.20	2 140
5	1.46	1.150	32	0.278	0.62	2 340
6	5.13	2.800	36	1.077	2.30	2 680
7	2.80	2.400	35	0.560	1.80	2 440
8	4.25	2.200	34	0.654	1.50	2 520
9	1.20	1.000	20	0.200	0.80	1 920
10	2.65	2.100	32	0.480	1.70	2 540
11	0.80	0.800	20	0.600	0.10	1 420
12	2.87	2.100	34	0.520	1.74	2 560

scope and the biggest subsidence value are added, and the biggest subsidence value appears in the center of mined-out area. The subsidence maximum value for those four monitoring region within five excavation step in *z* direction is shown in Table 2.

It can be known from the data in Table 2 that the surface subsidence curve is basin shape distribution, the sink value of −830 monitoring is far greater than the sink value of the other monitoring, with only the tiniest gap sinking value, almost consistent. Predictably, the coupling of the discrete medium and the shape medium happened in −830—−680 m. This coupling can very well control the sinking layer shape medium in certain limits.

Figures 5 and 6 show the displacement stress isoline of five excavation step at y=750 m profile (profile along the face towards).

It is known by *z*-displacement (Fig. 5) that coal floor obvious hooves-up. With the increase of the mining depth, the influence sphere of roof and floor increase gradually, but the impact of depth and height remain stable, the depth and height is about 10−14 times of coal seam thickness, the strata of the zone was heavily destroyed, caving zone located in above coal seam 60 m.

It is known by SZZ (Fig. 6) that the stress area

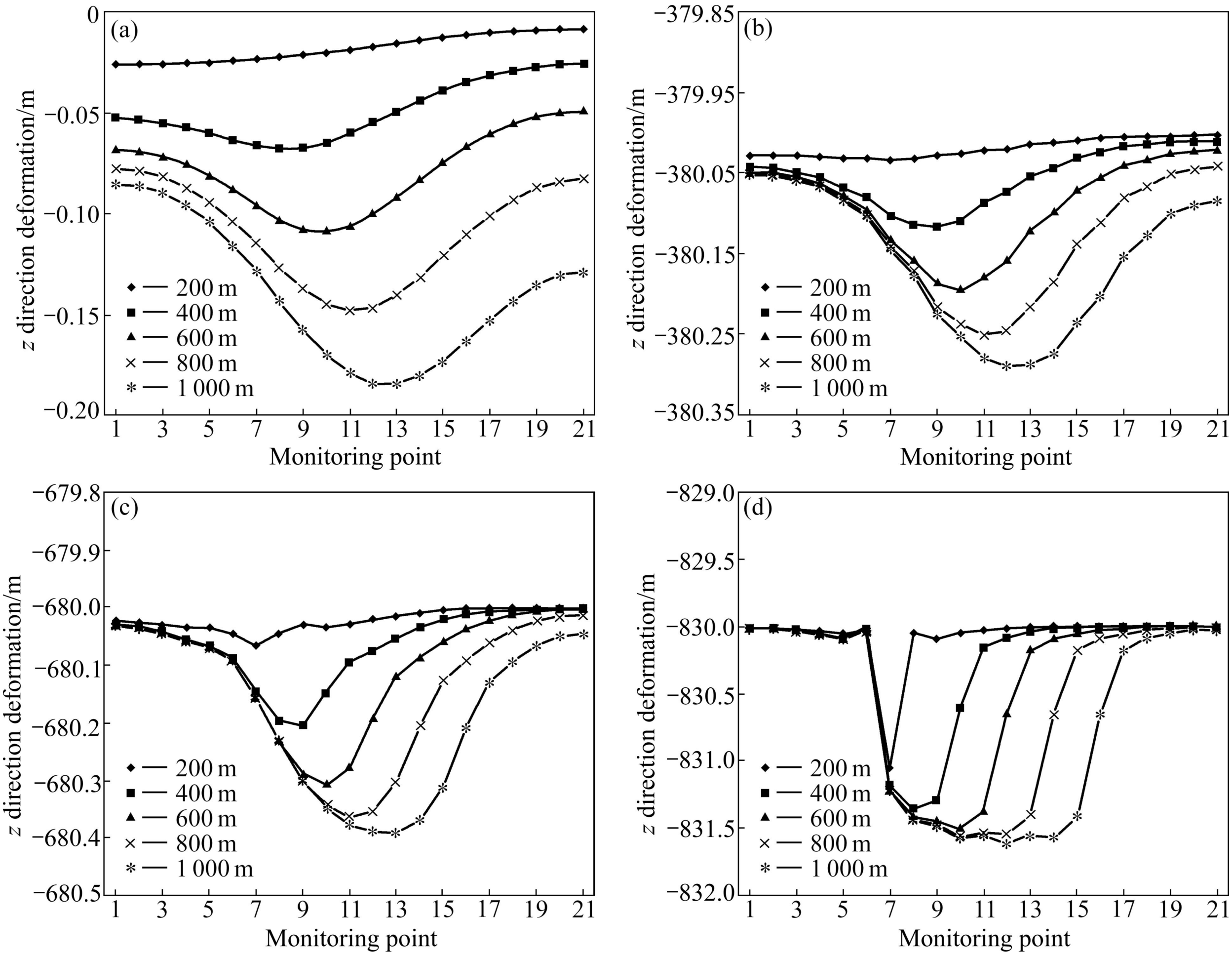

Fig. 4 *z* direction deformation map of different distances monitoring: (a) Surface; (b) −380 m; (c) −680 m; (d) −830 m

Table 2 Subsidence maximum values of four monitoring region

Monitoring distance/m	Subsidence maximum value				
	200 m	400 m	600 m	800 m	1 000 m
0	0.026 2	0.068 0	0.109 0	0.147 8	0.184 6
−380	0.033 7	0.118 4	0.194 1	0.251 2	0.290 4
−680	0.066 2	0.205 6	0.307 0	0.364 4	0.391 3
−830	0.051 0	1.370 0	1.506 0	1.578 0	1.615 0

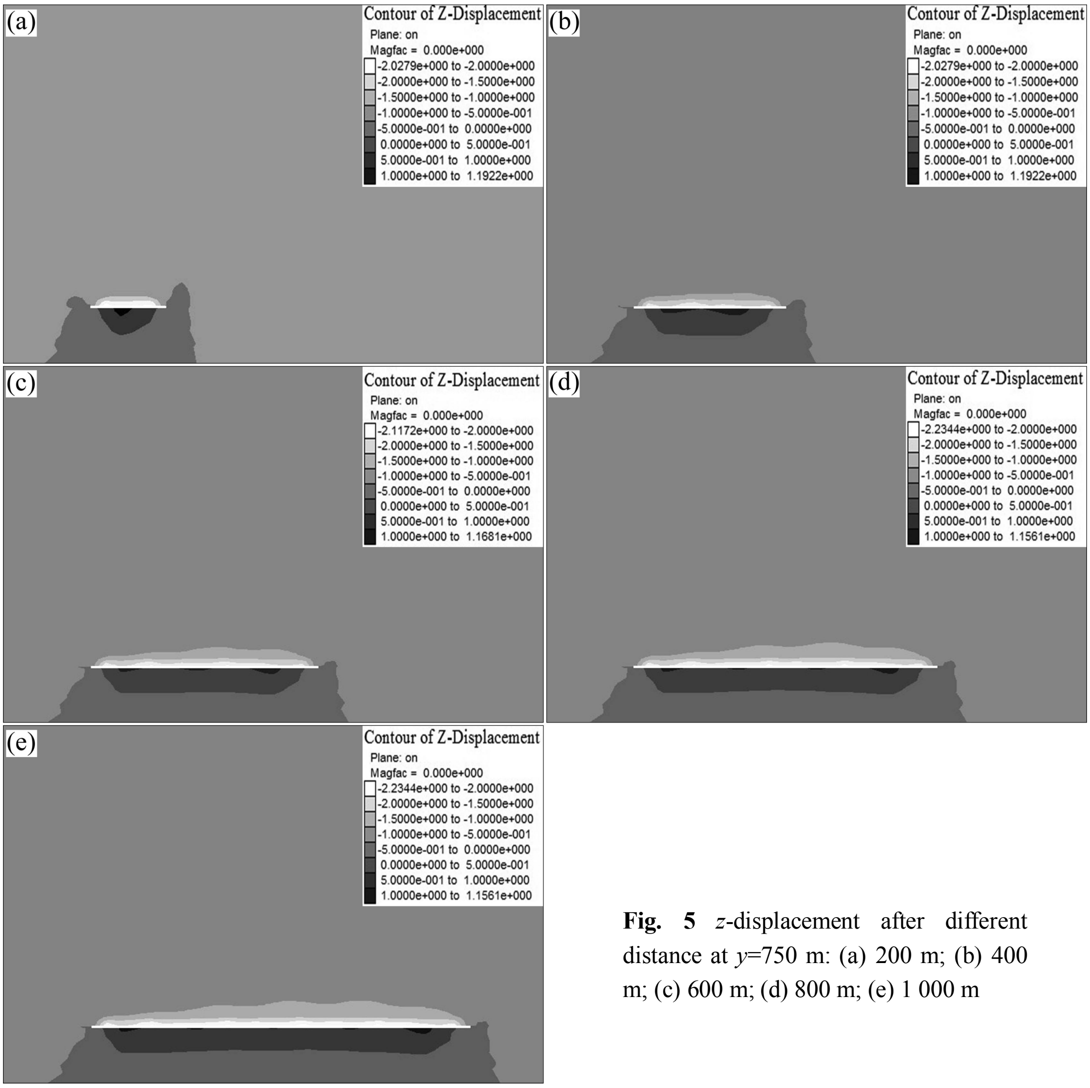

Fig. 5 z-displacement after different distance at y=750 m: (a) 200 m; (b) 400 m; (c) 600 m; (d) 800 m; (e) 1 000 m

influence continually expands along the mining direction, in position of above roof about 15−20 times coal thickness, stress layered distribution, the lower stress distribution is more complex.

Combined with the above analysis, it can be inferred that discrete medium and the layered media coupling zone located at right of roof about 15−20 times coal thickness. The next strata height in the upper boundary has about 20 times of coal thickness. The displacement change of the lower strata is the biggest about 1.6 m, but displacement greatly reduces above the strata. The change of stress in the coupling zone shows that the bending zone located over the coupling zone with layer structure, discrete medium located in the bottom of the coupling zone.

4 Conclusions

1) When deep mined, strata rock deformation mechanism obviously shows the zoning phenomenon, the zoning position and height is quite different from the shallow coal seam mining, different properties between layers of the coupling effect is remarkable.

2) The deep mining strata composite medium by coupling model is set by plate theory and discrete medium theory. Deep mining is simulated through 3-D numerical value by the FLAC^{3D} finite difference software and analysis of overburden rock of the coupling relationship between composite layer and the position of the coupling layer. Under the deep mining condition, in the roof above to adopt thick 10−14 times, the scope is for caving zone, in the roof by thick 20 times above is for bending belt, coupling area is located in the place where coal seam roof with the thickness of 15−20 times.

3) Considering interlayer effect of coupling zone corresponds to strata movement regularity and deformation mechanism and improves the prediction precision of surface subsidence.

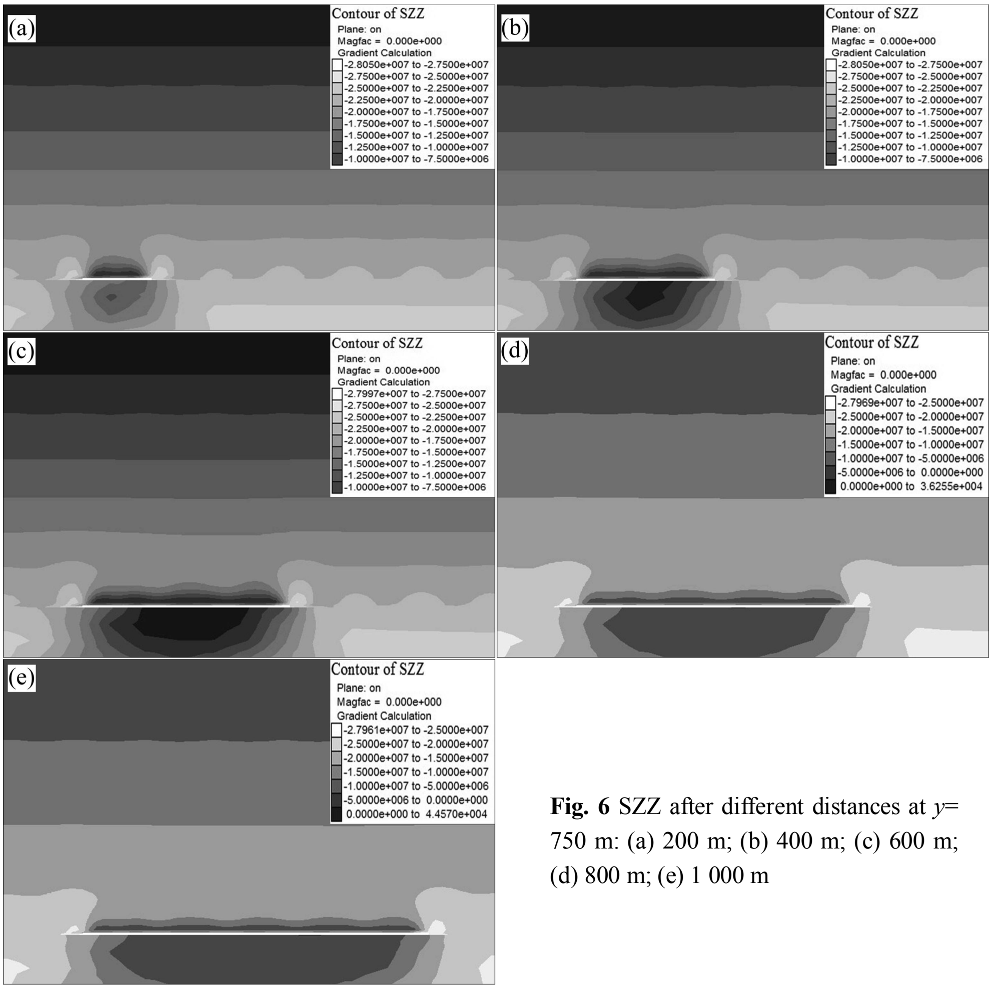

Fig. 6 SZZ after different distances at y=750 m: (a) 200 m; (b) 400 m; (c) 600 m; (d) 800 m; (e) 1 000 m

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