Behavior of Stress Field in Packed Bed of Kokura No. 2 Blast Furnace during Filling and after Blow-in

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As the first trial in the world, the stress field in Kokura No. 2 Blast Furnace during filling and after blow-in was measured. The characteristics of transitional behavior of the measured stress field is as follows: 1) In filling process, the vertical stress at the tuyere level increased with amount of charged burden, but the rate of increase gradually dulls. 2) The high stress was observed at the central part of the furnace in comparison to the intermediate. 3) After descent occurred by the blast start, the vertical stress remarkably increased at the furnace center. 4) The origin of the change of stress field appears to be located at tuyere region as a sink of burden and the change propagates toward the furnace center.

The simulation based on elasto-plastic theory reproduces the measured value well, and the validity of the simulation method was confirmed. By use of the simulation method, the mechanism of the transitional change in stress field after blow-in is also discussed. Before blow-in, the region in passive state is not found in the furnace, and the yield region appears a little at peripheral part of the upper shaft and belly. As the descent occurs, the arched field of stress is formed above tuyere, and one end of the arch is located at the bosh wall, and the other end heads for the furnace center, i.e. deadman. The remarkable increase of the vertical stress at the furnace center after blow-in is supposed to be induced by the growth of the arch.

KEY WORDS: blast furnace; stress field in packed bed; measurement; load cell; numerical analysis; elasto-plastic theory.

1. Introduction

The stress field in packed bed of blast furnace is the important factor which affects the stability of burden decent,1) the degradation of coke2) and softening and fusion behavior of the ore.3) Therefore, it is indispensable for improvement of the performance of blast furnace to grasp the characteristics of the stress field in blast furnace and optimize the operational conditions based on it. Many investigations4–8) have been made to clarify the behavior of the stress field in the furnace and the cold experiments of the blast furnace using scale models have played a key role in the investigations. For example, Shimizu et al.5) carried out measurement of stress distribution in a blast furnace scaled model by use of self-made earth pressure gauge and clarified features of the stress field in blast furnace by analysis of plasticity theory. On the other hand, Katayama et al.8) have developed the analytical method based on elasto-plastic theory as a technique which estimates stress field in blast furnace, and the verification of its validity was also carried out by using a cold scale model experiment.

As mentioned above, though the whole aspect of stress field in blast furnace has been clarified by using scale models, the direct verification according to the real furnace data has not been carried out. In this paper, the vertical stresses measured in Kokura No. 2 Blast Furnace (3rd campaign) during filling and after blow-in are shown and the characteristics of transitional behavior of the measured stress field are discussed. In addition, the verification of numerical analysis based on the elasto-plastic theory is also carried out.

2. Method of Stress Measurement

The stress probe is disc shape and has 3 load cells installed inside, and detects the vertical load acting on the upper surface, as shown in Fig. 1. The load cells are chosen to have a sufficient pressure proof, based on the stress value of packed bed estimated by means of numerical analysis mentioned later. The diameter of the stress probe was so determined that the more than 100 coke particles can be placed on the load detection plane and the probe can be carried into the inside of the furnace through the manhole for tuyere. Before burden filling, the probes were placed on the lumber, as shown in Fig. 2, to make the load detection planes coincided with the horizontal plane. The top view of probe layout is shown in Fig. 3. The outputs of the probes were recorded through the cables which rose up in the furnace and went out of the furnace at the top. Measurements were made during burden filling and about 5 h after blow-in.
3. Results

3.1. Filling Procedure

Burden filling of Kokura No. 2 Blast Furnace (3rd campaign) was carried out from April 6 to 9 of 2002. Figure 4 illustrates the schematic layer structure of filling, which is converted into the level layered state. Up to 22nd charge, only coke was charged, and ore to coke weight ratio (namely “O/C”) of burden was gradually increased in the following charges, and the O/C for last 4 charges were set around 4.5 corresponding to the usual operation. The total amount of charged burden was 1 597 t of which volume was 1 810 m$^3$.

3.2. Behavior of Stress during Filling

Figure 5 shows the change of vertical stress value measured by each sensor during filling. Here, the vertical stress means normal stress acting on the horizontal surface. According to the figure, the vertical stress at tuyere level in-
creases as the filling progresses, and the vertical stress at the furnace center was higher than that at the intermediate. There are some differences between the measured data of probes at the intermediate positions, 2.3 m and 2.5 m from the center. It seems to be a cause that the horizontal of the load detection plane could not be kept by the impact in the burden charging. It is noticeable that the stress value increasing initially with the burden charge tends to gradually decrease after the 35th charge and the coke dump of 44th charge when there were time intervals to the next charging. Figure 6 shows the variation of the measured stress with the amount of charged burden and the hydrostatic pressure line is also drawn in the figure. Though the measured stress increased with the amount of charged burden, the rate of the increase gradually dulls as the filling progresses. The measured stress values surpass the hydrostatic pressure in the initial stage of filling. This is supposed to indicate that the stock level in the range over the intermediate from the central part is higher than at periphery.

3.3. Transitional Behavior of Stress after Blow-in

Kokura No. 2 Blast Furnace was blown in at 14:00 of April 10th 2002, and started 3rd campaign. Figure 7 shows the transitional behavior of the stress distribution after blow-in. When the burden descent occurs by the blast start, the bottom stress increases again, after it decreases with the first increase, and especially, the increase of stress at the central part is remarkable. The phenomenon similar to this was also observed by the cold model experiment. This indicates that the stress field in the furnace changed with shifting from fixed bed to the moving-bed. In addition, the first increase in stress appeared in the intermediate part in advance to that of the furnace center, and therefore, it is estimated that the origin of the change of stress field is located at tuyere region as a sink of burden and it propagates toward the furnace center as well as upward.

In Fig. 7, there exists a phenomenon that the measured stress value of each sensor increases rapidly right after the blast started, as pointed with arrows (①, ②). In the fundamental study by use of the cold model experiment, the similar behavior was also observed immediately after burden descent, therefore this phenomenon is supposed to be caused by the sudden movement of burden which was induced by burnout of the lumber at tuyere.

The further discussion based on numerical analysis will be made in the following section.

4. Discussions

4.1. Bulk Density of Charged Burden

On the basis of weight of charged burden and measured stock line during the filling process, the bulk densities of coke and sinter beds in the furnace are estimated, respectively. Since the deposit surface profile is uncertain, in the estimation it was assumed that the deposit angle was 30° as a representative value and the stock line measurement data was converted into the value corresponding to flat surface. The result is shown in Fig. 8.
The estimated bulk densities of deposit burden (i.e., 640 kg/m³-bed for coke, 1750 kg/m³-bed for sinter) are larger than the numerical values used in the burden distribution estimation. This result indicates that the effect of the bed compaction by the load is significant. In the following numerical analysis of the stress field, the surface profile of charged burden was assumed flat, as shown in Fig. 4.

4.2. Validity of Elasto-plastic Analysis

Vertical stress field of the filling process estimated from the elasto-plastic analysis is shown in Fig. 9. Calculation conditions are listed in Table 1. As for inner furnace profile, the existence of the lumber installed for the tuyere protection was taken into consideration in the analysis as shown in Fig. 2. As shown in Fig. 9, the contour lines of vertical stress are approximately horizontally parallel until the stock level reaches the shaft, however, in the peripheral region from the lower bosh over the lumber, the vertical stress increases because of the bosh wall and the lumber undertaking a part of the burden load. Especially, the existence of the lumber in the filling seems to have a non-negligible effect on the stress distribution, that is, it causes that the stress output value of the sensor installed at the intermediate is lower than that of the central part.

In the final stage of the filling, the vertical stress at periphery of shaft division is smaller than that at central part of the equal level, as shown in Fig. 9, suggesting the effect that a part of the packed burden load dissipates by the diverging shape of the shaft wall is coming out.

Figure 10 shows the calculated values of the vertical stress at the tuyere level in the same manner as Fig. 9, and the measured data are also plotted for comparison. The correspondence is approximately good as a whole, though the calculated value appears to surpass the measured one in the filling initial stage. It can be said that the elasto-plastic modeling is valid for the simulation of stress field in real blast furnace. In the following, the numerical simulations based on elasto-plastic modeling are used to make further discussions.

4.3. Formation Process of Stress Field in Moving Condition

Figure 11 shows the simulation result of the steady vertical stress field after blow-in with the stress field at the filling completion. In the simulation, the lumber installed for the tuyere protection is assumed to disappear immediately.

Table 1. Calculation conditions.

| Item                      | Coke | Sinter |
|---------------------------|------|--------|
| Bulk density (kg/m³)      | 640  | 1750   |
| Angle of internal friction (deg.) | 32   | 32     |
| Angle of friction between solid and wall (deg.) | 20   |        |
| Young's modulus (MPa)     | 5.0  |        |
| Poisson's modulus (-)     | 0.3  |        |

Fig. 8. Transition of stock level during filling process.

Fig. 9. Simulated vertical stress distribution in the furnace.
after blow-in. When the burden descent occurs by start of blast, the static stress field changes remarkably and the stress at the center of furnace increases drastically, coinciding with the result as shown in Fig. 7. The radial distribution of measured vertical stress at tuyere level which is shown in Fig. 12 become steep after blow-in and will approach the saturated distribution finally, though the final value could not be determined experimentally by disconnection of the probes.

Then, the mechanism of the transitional change in stress field after the burden descent start is examined. Figure 13 shows the simulation result on the transitional change of vertical stress value at tuyere level. As shown in this figure, the vertical stress at the intermediate position once increases after the start of burden descent and changes to decrease, while the vertical stress at the center monotonously increases and the stress at peripheral part monotonously decreases to approach very small value.

Comparing Fig. 13 with Fig. 7, though there is no measurement at peripheral part, similar features are found for the behavior of the measured and simulated values of both intermediate and central part. This proves that the simulation based on the elasto-plastic modeling is also valid on the estimation of the transitional stress field of real blast furnace. However, as for the transition rate, the simulation result is considerably rapider than the experimental one. The same discrepancy as mentioned above was also observed in the model experiment of previous work.8) In the actual packed bed, it is supposed that time is needed for the change of stress field, that is, for the reconfiguration of packed particles, while the state transition rapidly progresses in the simulation based on the continuum.

Figure 14 shows the transition of vertical stress distribution in the furnace after blow-in. With this figure, there is seldom the change of the stress field in shaft division after

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Fig. 10. Comparison of simulated vertical stress with measured one.

Fig. 11. Transition of vertical stress distribution after blow-in.

Fig. 12. Transition of vertical stress distribution at tuyere level.

Fig. 13. Transition of vertical stress at tuyere level after blow-in.
the descent occurs. In the lower furnace region, the stress pattern gradually changes, that is, the stress concentrates in the furnace central region, while the relaxation of the stress progresses in the region in front of tuyere. Therefore, the transitional behavior of vertical stress at the intermediate position which is mentioned above is understood as follows. Increase of the vertical stress at the intermediate right after descent started is due to the effect of stress concentration to the central part of the furnace, and following decrease of the vertical stress occurs when the effect of the stress relaxation in front of the tuyere reaches the intermediate region.

Figure 15 shows the behavior of yield/non-yield region evaluated from the simulated results of the stress field distributions before and after blow-in. The judgment of yield or non-yield was done as follows. As illustrated in Fig. 16, the Mohr’s circle was drawn based on the stress values, in each position, and then, the angle \( \theta \) between \( \sigma \)-axis and the tangential line drawn from the origin to the Mohr’s circle was obtained, and the stress states was determined non-yield, if this value is smaller than the internal frictional angle \( \phi \) (32°) of packed bed. In Fig. 15, “nearly yield” region where the angle \( \theta \) is less than 32° and greater than 30° is also shown. As shown in the figure, before blow-in
yield region appears a little at peripheral part of the upper shaft and belly, after burden descent occurs by blow-in, the yield region appears in the region in front of tuyere and expands to the whole area of the lower furnace.

Figure 17 shows the behavior of the change of active and passive region in stress state. The active region indicates the region where vertical stress surpasses horizontal stress, and the passive region indicates the region in the reverse stress state. In addition, "nearly passive" region, where the ratio of horizontal stress to vertical stress is less than 1.0 and greater than 0.8, is also shown in the figure. Though the passive region is not found before blow-in, after the descent occurs, the passive region appears centered at the position in front of tuyere and expands to whole area of the lower furnace. Figure 18 shows the transitional behavior of the
maximum principal stress field in the furnace. As the descent occurs, the arched field of stress is formed above tuyere, and one end of the arch is located at the bosh wall, and the other end heads for the furnace center, i.e. deadman. The remarkable increase of the vertical stress at the furnace center after blow-in is supposed to be induced by the growth of the arch.

5. Conclusion

As the first trial in the world, the stress field in Kokura No. 2 Blast Furnace during filling and after blow-in was measured. The characteristics of transitional behavior of the measured stress field is as follows: 1) In filling process, the vertical stress at the tuyere level increased with amount of charged burden, but the rate of increase gradually dulls. 2) The high stress was observed at the central part of the furnace in comparison to the intermediate. 3) The phenomena in which the vertical stress value gradually decreased were observed after burden charge. 4) After descent occurred by the blast start, the vertical stress remarkably increased at the furnace center, and at the intermediate position, the vertical stress once increased and then changed for the decrease. 5) It is estimated that the origin of the change of stress field is located at tuyere region as a sink of burden and it propagates toward the furnace center as well as upward.

The simulation based on elasto-plastic theory reproduces well the measured data in filling process and after blow-in either, and the validity of the simulation method was confirmed by the real furnace data. By use of the simulation method, the mechanism of the transitional change in stress field after blow-in was examined. As the descent occurs, the arched field of stress is formed above tuyere, and one end of the arch is located at the bosh wall, and the other end heads for deadman. The remarkable increase of the vertical stress at the furnace center after blow-in is supposed to be induced by the growth of the arch.

The mathematical simulation methods will be applied to the optimization of operational conditions of present blast furnaces in service and, furthermore, profile designs of future furnaces.

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