Korean J. Crop Sci. 51(6): 539~543(2006)

Algebraic Analysis for Partitioning Root and Stem Lodging in Rice Plant

Jae-Ki Chang*†, Un-Sang Yeo, Jeom-Sig Lee***, Byong-Geun Oh**, Jeong-Il Kim**, Sae-Jun Yang***, Yeon-Chung Ku**, Ho-Yeong Kim**, and Jae-Keun Sohn******

*International Technical Cooperation Center, R.D.A., Suwon, 441-707, Korea
**Yeongnam Agricultural Research Institute, N.I.C.S., R.D.A., Milyang, 627-803, Korea
***National Institute of Crop Science, R.D.A., Suwon 441-857, Korea
****College of Agriculture, Kyungpook National University, Taequ 702-701, Korea

ABSTRACT : Lodging is classified as root lodging caused by the loss of supporting force in the root, bending caused by the deformation of the stem and breaking where the stem breaks down as loads exceeding critical elasticity were applied. This research excluded breaking which is not in a state of equilibrium and tried to partition the level of lodging using an algebraic model in root lodging and stem lodging, or bending. When a vertical load was applied, the deformation of the stem of rice plant showed the form of a quadratic equation. The trace of the panicle neck in the process of lodging was an ellipse-shape. When loading was pure root lodging, the trace of the panicle neck became a circle of which culm length is the radius. When it was a pure stem lodging, the trace of the panicle neck is an ellipse of which major axis is culm length and minor axis is 0.64*culm length. When both stem lodging and root lodging occurred in a natural setting, the partitioning of lodging can be calculated by a formula using eccentricity of an ellipse, S=e*100/0.768(S is the ratio of stem lodging in the whole lodging, e is eccentricity of the ellipse). This method is expected to be useful in simple lodging partitioning. We could also calculate the partitioning of stem lodging and root lodging as units of angles as an accuracy method, by using a straight line calculated by differentiating a quadratic equation of stem deformation at the origin of the coordinates. These two methods for dividing root and stem lodging showed different values. However, each of them showed almost same values with different lodging degree in one plant.

Keywords: rice, lodging, lodging partitioning, root lodging, stem lodging

All structures with weight and shape on the Earth are bound to experience deformation. Deformation ultimately leads to failure of a structure. That is not just because of dead load, meaning the weight of the structure itself, but also because of various loads continuously applied to the structure from the outside world, like rain and wind. A plant is also a structure with weight and shape existing on the Earth, which, unlike artificial structures such as buildings, goes through growth and development as a living creature. However, it is clear that a plant is also a structure that ceaselessly gets loads. A typical deformation a plant experiences due to loads is lodging, which has a huge influence on crop production. In the case of rice plant, the plant is the heaviest between heading and harvest periods, or from August to September, a time when Korea's weather conditions get such heavy loads from outside as typhoon and rainfall(Lee *et al.*, 1991). Lodging comes in two forms. Bending or breaking of stem is common in transplanting cultivation, while root lodging is frequently found in direct seeding cultivation(Kim *et al.*, 1993).

Lodging causes various forms of damage, such as viviparous germination, poor maturation, damage from harmful insects. It also requires extra efforts and money from individual farmers to put lodged rice plants back up. As it becomes hard or impossible to use combine for harvest, output decreases even though input increases. In addition, in direct seeding cultivation, lodging is more serious than in transplanting cultivation, restricting individual farmers from increasing acreage under direct seeding cultivation(Kim *et al.*, 1993).

To divide rice lodging with two types, we added artificial vertical load to the stem of rice plant at heading stage. Two type of lodging is classified with the shape and deformation point of lodged rice plant in this study. One is stem lodging caused by stem failure, and the other is root lodging caused by root failure from inside and outside loads.

MATERIALS AND METHODS

This study was carried out by employing a japonica rice variety, 'Dongjinbyeo'. The presoaked seeds were sown in a seedling tray. Twenty five days after sowing, seedlings were transplanted with one plant per pot into a pot(15cm diameter and 25cm high) filled with paddy soil, at May 25 in 2001. The transplanting depth was tried to maintain less than 1cm

†Corresponding author: (Phone) +82-54-732-2026 (E-mail) changjk @rda.go.kr
<Received August 10, 2006>

to make the same condition as direct seeding cultivation, although it was transplanting condition. Fertilizer was applied as 11-6.4-7.8 kg/10a of N-P_2O_5-K_2O. Other cultural practices were conducted according to standard cultural methods developed by Yeongnam Agricultural Research Institute, NICS, RDA.

The treatment was preformed with modified method of Tateno and Bae(1990) at the end of heading stage of rice plant. All tillers except for the largest one were removed form the base part of stem, and leaf blade except flag leaf were also eliminated from the tiller before treatment. These pretreatments were conducted to prevent any interference by other tillers or leaves. Hand made lead weights to apply a vertical load to the plant was used. The weights were 2 g or 5 g, as shown in the Fig. 1. The weights were hung on three points; the neck of panicle, a 25cm point from the ground, and the middle of the two points. The weights were added to each point until treated rice tiller failed to support from outside of vertical load. Adding the weights, we take care to prevent the plant from getting extra loads. We installed a 5cm-scale ruler to the pot to calculate an actual length during image analysis. (Fig. 1) Digital images from the beginning of lodging to the falling down of the plant were obtained from a digital camera. The camera was installed at the same height as the middle part of the plant.

Image J 1.31V (NIH, USA) was used for image analysis. The base part of the stem was set as the origin of the coordinates. Rice stems were located in the coordinates system using image analysis and algebra. An equation of the curve of deformed tiller was calculated with matrix function. The equation was considered as a quadratic equation which passes through the origin of the coordinates with four unknown coefficients. The stem bending equation is drawn from

$$x^2 + ax + bxy + cy + dy^2 = 0.$$

To find the four coefficients of the equation, five points on the stem including the panicle neck and the basal part of tiller were measured with image analysis program. A straight line which passes through the origin of the coordinates was calculated from differential calculus with the quadratic equation at the origin of the coordinates. This straight line is considered as standard line for dividing root lodging and stem lodging from total lodging. In addition, to find the trace line of the panicle neck, the top part of rice stem, creates while falling down, we calculated the equation of an ellipse, using the culm length and position of the panicle neck when the plant was deformed. The center of the ellipse is the origin of the coordinates. The culm length of the equation is the y coordinate when $x = 0$. To check the calculations, an equation graphing program, GrafEq (Pedagoguery Software Inc., Canada), was used.

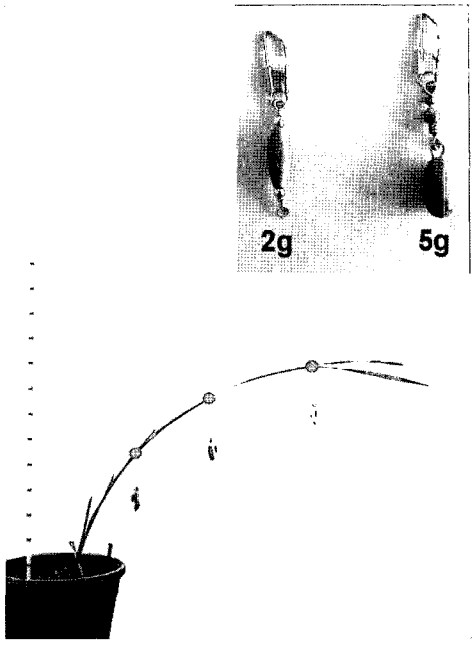

Fig. 1. Two kinds of lead weights and applying a vertical load to the rice tiller at the end of rice heading stage.

RESULTS AND DISCUSSION

Algebraic Model for Partitioning Lodging

When the stem of rice plant experiences lodging because of various loads, static load and dynamic load, the plant is bound to fall down due to fail to support rice body with stem and root. If the plant gets loads within critical elasticity of the stem, in this case, lodging occurs because of root lodging and bending (stem lodging). Meanwhile, there is another form of lodging caused by breaking, rather than the lost of supporting force in root, which occurs when force exceeding critical elasticity of the stem is applied. We excluded lodging caused by breaking in this experiment, as equilibrium of force breaks down in that case.

The lodging model in this study was developed with an ideal stem which has the uniform cross sections and physical features at all sections. In this case, the curve created when the ideal stem bends will be the form of an equation of a circle. If the lodging occurs purely in the form of root lodging without deformation of stem, the trace of the panicle neck is a circle with the radius of culm length. The equation is

$$x^2 + y^2 = b^2,$$

where b is culm length. When the panicle neck touches the ground, the equation of the stem is a straight line, of which $y = 0$, as there is no deformation such as bending. In this case, the distance between the base part of the stem and panicle neck is culm length. If the stem bends, a pure stem lodg-

ing, the trace of panicle neck becomes the shape of an ellipse of which axes are X-axis as the minor axis and Y-axis as the major axis. The equation is

$$\frac{x^2}{(0.64b)^2}+\frac{y^2}{b^2} = 1 ,$$

where b is culm length. This equation derived from deformation shape of rice stem when the panicle neck meet the ground by bending. The stem bending equation is drawn from

$$(x-0.32b)^2+y^2 = (0.32b)^2 ,$$

where b is culm length. The equation of a circle of which semi-circumference equals culm length. The constant 0.32 in the equation came from $1/\pi$ and 0.64 from $2/\pi$ (Fig. 2).

There are two ways of partitioning the level of root lodging and stem lodging in a lodged rice plant (Fig. 2). First, the level of deformation can be described with angles, by using the equation of a straight line calculated by differentiating the curve equation of the stem at the origin of the coordinates. When the stem fully lodged purely due to root lodging, the deformed curve of stem equals above-mentioned circle equation, and the equation of the straight line calculated by differentiating the circle equation at the origin of the coordinates equals $x = 0$. This means that the deformation angle by a pure stem lodging is 90°. If both root lodging and stem lodging occur, having the stem fall down, the whole lodging angle is measured by the angle between Y-axis and the straight line linking the panicle neck and the origin of the coordinates. The angle of the root lodging is measured by the angle between Y-axis and the straight line calculated by differentiating the curve of stem at the origin of the coordinates. The angle can be calculated by the formula, θ=atan(1/a), where a is x's coefficient of the equation of stem deformation.

Second, the line following track of the locus of panicle neck created by lodging can be used. If it is pure root lodging, the line equals a circle, of which radius is culm length, and the point the panicle neck of the rice touches the ground is culm length. If it is a pure stem lodging, it is an ellipse and the point the panicle neck touches the ground equals $x = 0.64b$ (b is culm length). The point that the panicle neck touches the ground moves from $x = 0.64$b toward $x = b$, as the ratio of root lodging in the whole lodging increases. Stem lodging caused by bending shows the opposite phenomenon to that. Therefore, as the level of stem lodging increases, the ellipse gets longish. The ratio or the level of stem lodging can be calculated by eccentricity of the ellipse. The eccentricity is calculated by dividing the focal length by the major axis of the ellipse (Eccentricity = focus/major axis). Focus of ellipse can be calculated by $a^2 = c^2 - d^2$ where a is the focus, c is the major axis and d is the minor axis. The value of eccentricity indicates the shape of figure from equation; 0 is a circle, smaller than 1 is an ellipse, 1 is a parabola and bigger than 1 is a hyperbola. If it is pure root lodging, the trace of the panicle neck equals a circle, of which eccentricity is 0. If it is pure stem lodging, eccentricity is 0.768. Eccentricity in lodging is between 0 and 0.768. When eccentricity approaches to 0, root lodging is more predominant than stem lodging. If eccentricity approaches 0.768, it is interpreted that stem lodging is predominant. Therefore, the ratio of stem lodging in the whole lodging can be described as the following formula:

$$S = \frac{e}{0.768}100 ,$$

where S is the ratio of stem lodging in the whole lodging and, e is eccentricity.

Grafius (1954, 1958) devised the lodging resistance formula of cLr=F/b (F=weight the culm is capable of supporting, b=height of a culm). He used an ellipse formula of $x^2/a^2+y^2/b^2=1$ to measure the trace line of the panicle neck of rice plant, as the prior stage to derive the formula. a equals the distance between the panicle neck and the base part of the stem, when a cereal crop fully lodged. In a lodging model using this ideal stem, the scope of a is between $0.64b$ and b, and the shape of ellipse approaches a circle, as

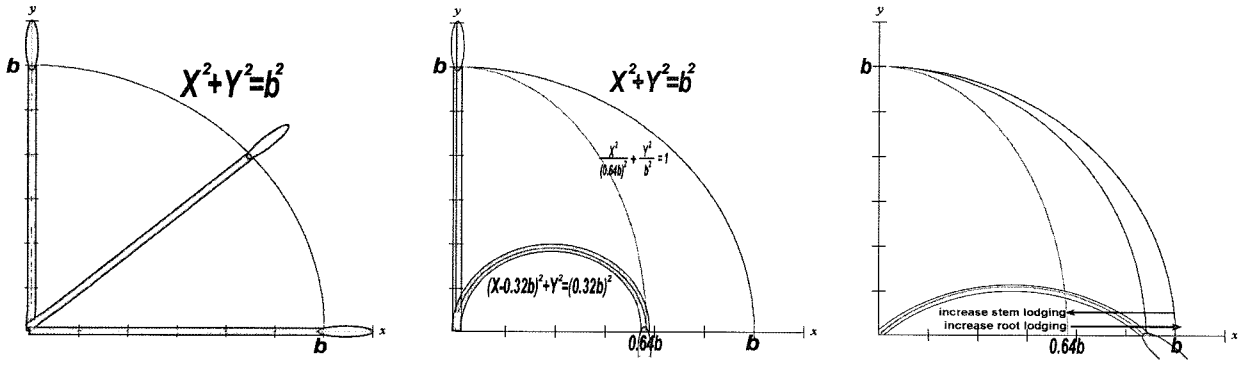

Fig. 2. Models for a pure root lodging (left), a pure stem lodging (center) and both root lodging and stem lodging (right).

the ratio of root lodging gets bigger. Eccentricity will be a useful tool in simply partitioning root lodging and stem lodging, as there is only need the trace equation of the panicle neck in lodged rice plant.

Application of the lodging model

Actually, the stem of rice plant is tapered beam-shape with a wide base and a narrow upper part, unlike the hypothesis we made above. The stem of rice plant consists of nodes and internodes, and multiple leaf sheaths are piled on it. Therefore, as there's no guarantee that it becomes part of a full circle, deformation of the stem is calculated by using a kind of quadratic equation, $x^2 + ax + bxy + cy + dy^2 = 0$. Each coefficient in the equation is calculated by matrix operation, using the information from images. If d equals 1, that signifies that the curve is a circle. The curve becomes a straight line, $y = -a / cx$, when differentiated at the origin of the coordinates. With gradient of this straight line, we calculated deformation angle by root lodging and stem lodging. Eccentricity of the ellipse was also measured, the trace of the panicle neck, and used it to measure the level of root lodging and stem lodging. In the natural condition, lodging occurs both in the stem and root.

The result of the algebraic analysis of the deformation occurring when the stem lodged is Fig. 3. Increasing vertical load from outside, the rice plant showed low level of deformation until critical load. When the applied load was larger than the bearing power against it, the rice plant was rapidly bended or broken down. In case of broken stem, the broken positions were various with first to fifth internode(data not shown). It was different result compared to natural condition(Hoshikawa&Wang, 1990; Wang & Hoshikawa, 1991), but similar with Hitaka and Krishnan(1963)'s report using rain load. Breaking of stem was excluded in this study. The critical load of used rice stem was about 41 g in this study. The quadratic equations, showing the level of stem deformation when 41 g, 42 g and 43 g of vertical force were applied to the stem, were $x^2 - 36.4x + 0.7xy + 2.8y + 0.3y^2 = 0$, $x^2 - 84.8x - 0.2xy + 14.2y + y^2 = 0$ and $x^2 - 63.0x + 0.5xy + 19.0y + 0.7y^2 = 0$, respectively. Coefficients of x showed minus sign in the formulas. It was shown that y's coefficient steadily increases, when the level of stem deformation gets higher. Quadratic curves are classified into a circle, an ellipse and a hyperbola. It can be classified based on the value of $4ac - d^2$, where a is x^2's coefficient, c is y^2's coefficient and d is xy's coefficient in the quadratic equation; 0 is a parabola, bigger than 0 is an ellipse including a circle and smaller than 0 is a hyperbola. The values of the equation $4ac - d^2$ in this experiment were 0.71, 3.96 and 0.70 respectively, meaning it is ellipse or circle, as all the figures are bigger than zero.

To divide lodging into two type as root and stem lodging, differentiation at the origin of the coordinates was conducted from the stem deformation equation. Coefficient of x of a straight line calculated by differentiating the equations decreased to 13, 6.0 and 3.3, as lodging is continuing. Total lodging angle is defined as the angle between Y-axis and the straight line between base part of stem and panicle neck. Root lodging angle is set by the angle between Y-axis and the straight line as a result of differentiation, and stem lodging angle is set by the value after root lodging angle is deducted from total lodging, the angle between two straight lines. Total lodging angle increased to 23°, 46° and 79°, respectively. Angles made by stem lodging were 18°, 37° and 62°, and the stem lodging ratio was 81%, 80% and 79%, respectively. The stem lodging angle was increased during lodging, but the ratio of stem lodging was almost same among various lodging degrees in a stem. The other method for partitioning of lodging was also analyzed. The trace lines that the panicle neck creates when the stem lodged were almost the same. The lines, depending on levels, were X^2 /

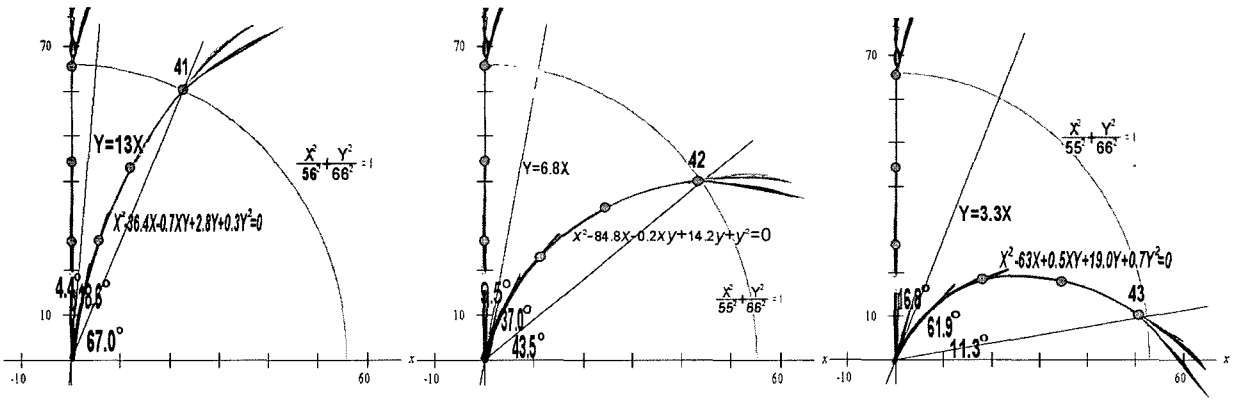

Fig. 3. Formulas and values for partitioning of lodging in actual lodging applied with vertical loads.

$562 + Y^2 / 662 = 1$, $X^2 / 552 + Y^2 / 662 = 1$ and $X^2 / 552 + Y^2 / 662 = 1$. The eccentricities of the three trace lines of rice panicle neck were 0.53, 0.52 and 0.52, respectively. The shape or size of an ellipse in the process of lodging did not change much. We calculated the ratio of stem lodging in the whole lodging, using a form made in this study and the result was 69, 71 and 71%, much the same figures. The plant used in this study showed that stem lodging was more predominant than root lodging, although the transplanting depth of was maintained as 1cm to make similar condition of direct sowing cultivation of rice. The load was applied with vertical direction on rice plant. It seems that vertical load mainly affect to stem lodging. Therefore, additional study need to be conduct with horizontal load like wind load and natural condition.

The values divided with angle were higher than the ratio of stem lodging calculated through eccentricity. That is probably because rice stem is not ideal stem with having uniform cross section and physical properties throughout its span. Especially, the stem of rice plant has thick base and thin upper part, which leads to unequal deformation ratio of stem at each part. This is thought to be the cause of the difference. When calculating the stem lodging ratio in the whole lodging using eccentricity, root lodging tends to be overestimated and stem lodging to be underestimated, but this is still useful method to divide total lodging with root and stem lodging as easy and simple method. The position of panicle neck and stem height is only needed to lodging partitioning with two type in lodged rice plant in eccentricity method.

REFERENCES

Grafius, J. E. and H. M. Brown. 1954. Lodging resistance in oats. Agron. J. 46 : 414-418.

Grafius, J. E. 1958. Observations on the lodging resistance formula. Agron. J. 50 : 263-264.

Hitaka, N. and R. H. Krishnan. 1963. Studies on lodging in rice. 3. the effect of rain on lodging. Rice news teller : 38-40.

Hoshikawa, K. and S. Wang. 1991. Studies on lodging in rice plants II. A general observation on lodged rice culms. Japan. Jour. Crop Sci. 59(4) : 809-814.

Kim, J. K., M. H. Lee, and Y. J. Oh. 1993. Lodging pattern of rice plant in broadcast-seeded and hand-transplanted cultivation. Korean J. Crop Sci. 38(3) : 219-227.

Lee, M. H., Y. J. Oh, and R. K. Park. 1991. Lodging mechanisms and reducing damage of rice plant. Korean J. Crop Sci.(RCD II) : 383-393.

Tateno, M. and K. Bae. 1990. Comparison of lodging safety factor of untreated and succinic acid 2,2-dimethylhydrazide-treated shoots of mulberry tree. Plant Physiol. 92 : 12-16.

Wang, S. and K. Hoshikawa. 1992. Studies on lodging in rice plants II. Morphological characteristics of the stem at the breaking position. Jpn. J. Crop Sci. 60(4) : 566-573.