DRAINTUBE PLOWS: Their Operation and Laser Grade Control

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"PLOWING-IN" corrugated plastic drainage tubing with plow-type equipment automatically controlled by a laser beam grading system, is a modern subdrainage method beginning to be used in several areas of the United States and Canada. The idea of installing drains with equipment called "Draintube Plows", is not new as discussed by Dr. van Schilfgaarde in his paper at this Symposium, regarding "Drainage—Yesterday . . .". The engineer's viewpoint has long been one of speeding up the installation of drains by eliminating the slow trenching and backfilling operations—most approaches taken have involved some adaptation of the "mole drainage plow".* The "plowing-in" of drains became practical, from a materials handling standpoint, with the introduction of coilable, corrugated-wall plastic drain tubing. In this method, the drainage tubing is merely "fed" into the ground through a slit opening created by passage of a blade through the soil, thus eliminating the conventional trenching. Soil erupted by the plow blade can be pressed down easily and rapidly by running a track of the crawler tractor over the slit opening after installation, thus eliminating backfilling. The high speed of installation is the major advantage of the "plow in" method; drain installation at a rate of 70 to 150 fpm ground speed, or 1,500 to 4,000 ft of drain laid per working hour, are typical with the latest equipment.

This paper describes the operational and/or performance characteristics of Draintube Plow equipment; criteria for mounting and/or adapting laser grade control equipment; efficient field work procedures; and areas requiring further equipment development work.

TYPES OF DRAINAGE PLOWS

Several different plow-type drainage machines have been developed but, basically, they fall into two groups as to the method of depth control, (a) depth-gage wheel, and (b) long floating-beam. The depth wheel type is best suited where the land slope is uniform and constant depth plowing can be used, such as on much of the irrigated lands of the Western United States. On irregular ground surfaces, it would be very difficult to accurately control the depth wheels fast enough to maintain grade in the drainage channel, especially at normal ground speeds of 70 to 150 fpm. Willardson (1970) discussed the use of a large depth-gage wheel controlled plow for installing corrugated plastic drains in the Imperial Valley, California. Further attention will not be given here to the depth-wheel type plow.

The long floating-beam type plow is well suited for operation on the irregular ground surfaces commonly encountered on most of our cropland. The floating-beam principle of operation is illustrated in Fig. 1. For the case shown in the schematic, a steady-state plowing depth is assumed and the hitch height is held constant above the average ground surface datum during forward motion. The counteracting rotational moments about the hitch pin (a pivot point) due to the plow weight (mg) and soil resistance (R) balance each other and the plow is said to operate with a "floating-beam action." Step changes in the vertical position of the hitch relative to the ground surface reference are not immediately reflected in the plowing depth. The plow blade adjusts or "floats" to a new equilibrium depth as the tractor moves forward; as much as 5 beam-lengths of ground travel may be required for the blade to reach a new equilibrium depth after a step-change in hitch height. This characteristic time-lag in response permits the use of conventional automatic feedback control of the plow's hitch height to maintain a desired drain channel gradient.

Fouss (1971) studied the basic response characteristics of a long floating-beam pole plow.† He found that in a silt loam soil, changes in plowing depth in response to changes in hitch height were approximately linear, but not directly proportional: for example, a ± 1-in. vertical displacement of the hitch (held constant after change) resulted in a ∓ 1.25-in. change in plowing depth (difference between steady state plowing depths). This characteristic response will occur for all drainage plows and is governed somewhat by plow blade design, but is influenced more by the changes in soil resistance on the moving blade as plowing depth changes. In general, the draft on a soil cutting blade can be expressed as a power function of depth; experience indicates that the draft function for many soils varies with the 2.0 to 3.0 power of depth. Again considering rotational moments about the plow hitch pin (pivot), one sees that the constant moment due to the plow weight is opposed by a soil resistance force mo-

†A portion of this study involved the mathematical modeling and analog computer simulation of the dynamic response of a floating-beam mole plow; these results will be published in a future paper.

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*A summary of drainage mechanization research will be available in the ASA Monograph 14, Drainage for Agriculture, Chapter IV: "Drain tube materials and installation," by J. L. Fouss (in preparation).

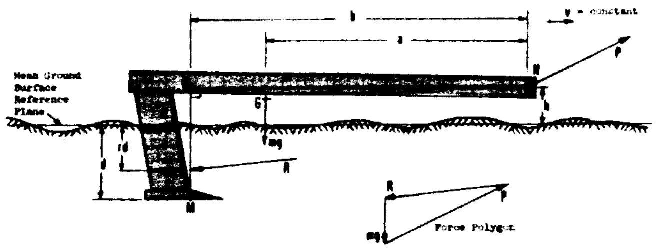

FIG. 1 Principal steady-state forces on floating-beam drainage plow.

ment that varies nonlinearly with plowing depth. Thus, the "floating" adjustments in plowing depth are greater than changes in hitch height. Therefore, for a wide range of topography, accurate grade control for the long floating-beam plow *cannot* be achieved by controlling the hitch such that it travels on a line parallel to the desired drain gradient, as assumed in earlier work (Fouss and Fausey, 1967; Fouss and Reeve, 1968; and Fouss, 1968). Proper control of the hitch motion for accurate grade control is discussed later.

DESIGNS OF FLOATING-BEAM DRAINTUBE PLOWS

A few crawler tractor drawn drainage plows developed and operational by the early 1970's, for the installation of corrugated plastic tubing, utilized the floating-beam principle. One of these plows, manufactured in England and called the "Badger Minor"‡, was patterned after a unique design developed by Ede (1961, 1965) in England. Actually this plow might be said to operate with a "floating blade" action. The blade and tractor are connected by a pair of rollers which run in a curved track that is mounted on the rear of the tractor. The center-of-curvature of this roller track acts as a virtual hitch point which coincides approximately with the center of the crawler tracks. The plow blade is thus nearly isolated from most pitching movements of the tractor. Depth and gradient are controlled by raising and lowering the imaginary hitch point; this is accomplished by hydraulically moving the roller track frame relative to the tractor mount. Thus the Badger Minor plow operates, in principle, as a long, floating-beam plow; other features of this plow are discussed by Prof. Irwin in his paper at this Symposium. A similar drainage implement called the "Zor Plow", developed in Canada, uses two nonparallel, "floating" links instead of the roller track to make the connection with the blade.

The draintube plow prototype shown in Figs. 2 and 3 was designed and developed by the authors§ under a USDA, ARS, SWC research project conducted cooperatively with The Ohio State University and the Ohio Agricultural Research and Development Center. The plow was fabricated under Government contract by the Process Equipment Company of Tipp City, Ohio. The basic plow design consists of a tool-bar mounted blade, through which 4-in. diameter corrugated plastic tubing can be installed to a 6-ft maximum depth in a medium clay soil. This requires a crawler tractor capable of developing at least 60,000 lb of drawbar pull; performance of the grade control system and ground-speed control are improved if the tractor is equipped with a torque converter type transmission. The twin draft links connected to the tool-bar ends serve as the long, floating-beam (split beam); each beam is hitched to the tractor at the rear side of the bulldozer blade. The draft links, or twin beams, were arched and extended above the crawler tracks so that the tool-bar length (width of plow frame) could be kept at 11 ft maximum to facilitate transporting the equipment. The two hitch points are spherical pivots, and the tool-bar to draft link connections each provide a vertical axis of pivot. Thus, the tool-bar and split-beam assembly can "swing" in a horizontal plane to permit steering the tractor or to lay curved drain lines, and in addition permits the plow blade to be maneuvered around buried stones. The plow's operating depth is regulated by raising or lowering the hitch points with the dozer blade; the same hydraulic cylinders used to position the dozer blade (above the ground level) thus provide depth control for the plow. The large hydraulic cylinder on the rear of the tractor is used only to lift the plow out of the ground and transport it; in plowing position this cylinder is put into a "floating" mode, that is, it carries no weight. Because of the downward pull component, having the hitch points forward of the tractor improves traction efficiency and dynamic stability of the crawler tractor. For the prototype plow, the hitch is about 24 ft forward of the plow blade, and can be positioned from 2 to 6 ft above the ground surface with the dozer blade. For any given height of the plow hitch above the ground, the plowing depth can be adjusted to the desired level by changing the angle between the tool-bar and draft links; large turnbuckle screws are provided to make this adjustment (see Figs. 2 and 3).

The structural members of the plow frame were designed with large cross-sections to create rigidity; springiness of the frame would cause severe problems in controlling plowing depth and thus drain gradient. The plow was constructed of T-1 type steel to provide high ultimate strength. The plow blade was designed to reduce soil resistance (draft) by applying the following concepts: (a) the upward sloping leading edge of the blade causes lifting of the soil as the blade passes through it, thus reducing soil cutting force; and (b) the thicker leading edge of the balde moves the soil aside sufficiently to reduce frictional drag on the relatively large surface area on the sides of the blade shank. The enlarged leading edge encompasses the corrugated tube feeding-guide (see Fig. 2). The use of a vibrating blade was not considered for this plow.// For drains larger than 4 inches in diameter, a separate tube-feeding tool can be attached behind the present blade. Corrugated tubing 5 and 6 inches in diameter probably can be satisfactorily installed in this manner, but installation of larger sizes is questionable.

Two smaller versions of this ARS plow design are envisioned, namely, a

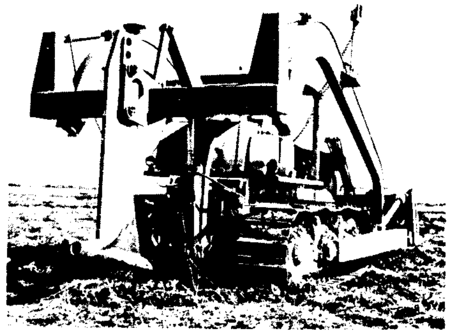

FIG. 2 ARS Draintube Plow in transport position.

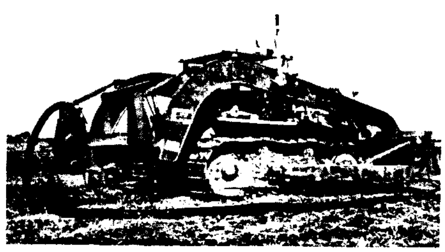

FIG. 3 ARS Draintube Plow in operating position.

‡Trade and company names are included in this paper for the benefit of the reader and do not imply endorsement or preferential treatment of the product listed by USDA.

§The authors wish to acknowledge the assistance of Mr. Zigbigniew Stolarczyk and Mr. Dennis Bassett who prepared the engineering design drawings, and special appreciation and thanks to Dr. Glenn Schwab for assistance and encouragement throughout the project. Furthermore, the authors gratefully acknowledge the loan of a large crawler tractor from The Caterpillar Tractor Co. for testing and evaluation of the prototype plow.

//A vibratory-type plow does reduce draft requirements, but not necessarily total horse power demands when the power unit to drive the vibrator is considered in the total. In many areas of the U.S., the smaller tractor used on a vibratory plow can be transported over highways without special permits and thus may prove quite advantageous.

medium depth plow (4- to 5-ft depth capability), and a shallow depth plow (3-ft maximum depth). These plows, of course, would be pulled by smaller crawler tractors than used on the prototype. The medium depth plow design would be used mainly in the Midwest, whereas the prototype plow developed for the design testing program would be used mostly in the Great Plains states and western regions where deep drainage is needed in conjunction with irrigated lands. The shallow depth plow might be considered still experimental, in that its use to install small diameter, shallow, and closely spaced corrugated plastic drain-tubes looks promising for subdrainage of heavy clay and/or fragipan soils.

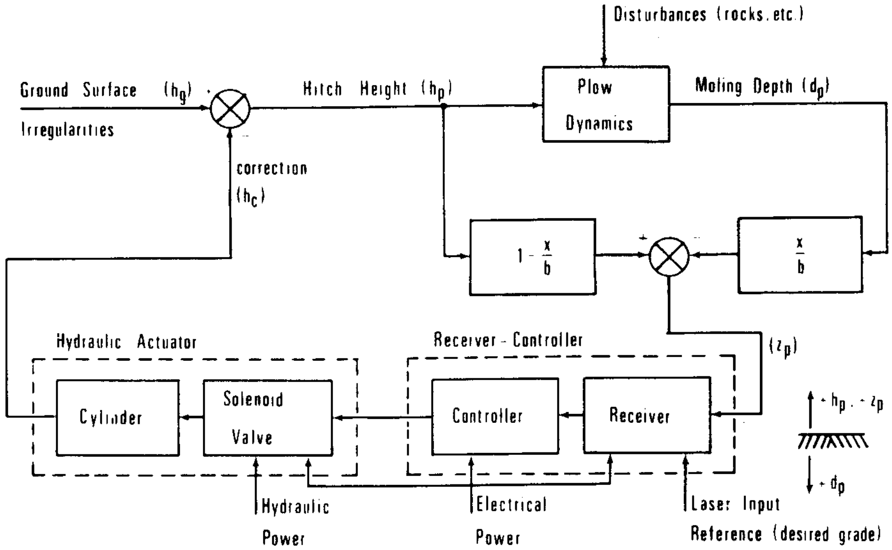

FIG. 4 Block diagram of plow and laser depth-and-grade feedback control system.

ADAPTING LASER AUTOMATIC DEPTH AND GRADE CONTROL SYSTEMS

The successful operation of high-speed plow-type drainage equipment is dependent upon the ability to control and maintain the gradient of the drain-tube installed (Fouss, 1965). One of the first experimental laser beam automatic grade control systems was designed to meet the requirements for the draintube plow equipment (Fouss and Fausey, 1967; and Fouss, 1968). Commercial versions of laser beam grading systems became available, however, before operational drainage plows and the new automatic systems soon were accepted and used by contractors on conventional trenching machines.

The basic principle of automatic depth and grade control for a draintube plow using a projected laser beam datum (grading reference), and an on-board laser tracking-receiver which automatically controls plowing depth via hydraulics, has been previously reported (Fouss, 1968). The same principle of auto-control applies to the conventional wheel-type trenching machine that is equipped with a "shoe". However, the difference in normal ground speed between the trencher and plow (i.e., 15-25 ft per min and 70-150 ft per min, respectively) makes it necessary to consider the machines independently when adapting or mounting a laser system for automatic grade control. Here the draintube plow will be discussed in considerable detail to illustrate the importance of various factors and system parameters considered in the control system adaptation.

The prototype ARS draintube plow (Figs. 2 and 3) was equipped with a "laserplane" type of automatic grade control system produced by the Laser-plane Corp. of Dayton, Ohio (Studebaker, 1971). In this system, an elevation reference plane is generated above the working surface by rapidly rotating (5 cps) the projected laser beam (much like a lighthouse beacon), where one axis in the plane is aligned parallel to the desired drain gradient, and the cross-axis is aligned either horizontal or parallel to the general land slope. The effective range of the rotating "laser beacon" is at least 1,000 ft, and thus the laser elevation reference plane covers a large field area with each setup of the laser transmitter (e.g., a field within a 75 to 100-acre circular area).

The laser tracking-receiver, mounted on the plow frame (Fig. 3), consists of a vertical array of closely spaced photo-cells, which are connected to a logic and controller circuit. The controller in turn operates the tractor's hydraulics to raise or lower the plow hitch (by moving the dozer blade up or down) to provide the corrective feedback control motion, and thus automatically maintains the receiver nearly centered on the laserplane reference. The laser receiver unit is very sensitive and can electronically detect the center of the 1-in. thick (approximate) laserplane reference within a "dead zone" of about ±1/16 in. However, the proper use of this electronic detection signal in the feedback control system is most important to achieve stable and yet accurate automatic grade control.

The draintube plow and laserplane (or laser beam) feedback control system can be represented in block diagram form as shown in Fig. 4, where b is the plow's beam length (Fig. 1), and x is the distance rearward from the hitch to the laser receiver unit mounted on the plow beam (Fig. 3); symbols for other variables are identified in Fig. 4. For the "Laserplane" system, the receiver-controller output is digital; either an up-, down-, or no-correction "signal" is generated every 200 msec. (i.e., for each rotation of the "laser beacon"). The solenoid valve and hydraulic cylinder (which cause the hitch to move up or down) are thus operated in an on-off (or step-wise) manner by the digital output of the controller unit. Since the sole-

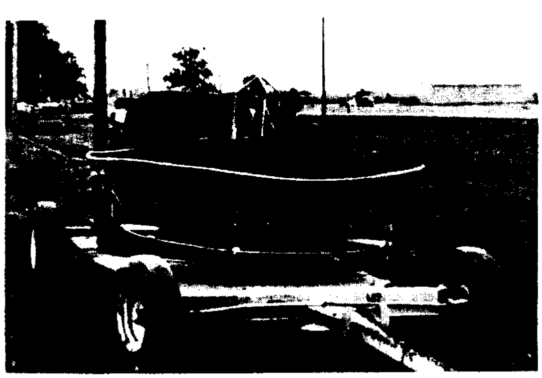
FIG. 5 Wagon-mounted uncoiling mechanism for corrugated plastic drain tubing.

noid valve opens and closes with a characteristic time-delay relative to the inputs from the controller, the duration that the controller unit "holds" the valve open (for an up- or down-correction) is important to system performance. For the prototype draintube plow, the controller was factory adjusted such that up- or down-correction signals were held "on" for 180 msec. out of 200 msec.** The time-delay of response for the solenoid valve was greater than 20 msec., therefore, the automatic system operated essentially as a pure "on-off" feedback control. The hydraulic flow rate from the pump was adjusted so that the hitch height would limit-cycle ("hunt") with an amplitude of 1 to 1-1/4 in. and at a frequency of 1/2 to 1 cps. Because of the long time-lag in response of the floating-beam plow to change plowing depth, the up-and-down cyclic motion of the hitch point at this amplitude and frequency does not cause significant variations in the drain channel gradient. This approximate "on-off" mode of control was predicted to be satisfactory for use on the draintube plow by Fouss and Hamdy (1970) from analog computer simulation studies of the feedback control system, and later by Fouss (1971) where the plow dynamic (Fig. 4) effects were also included in the simulation.

The above discussion relates to sensitivity and stability of the feedback control system, but possessing these two characteristics does not guarantee accuracy of grade control for the draintube plow, or any other drainage machine for that matter. Undoubtedly, one of the more critical factors relating to grade control accuracy is being able to determine the optimum position for mounting the receiver unit on the drainage machine's frame (i.e., the x/b ration in Fig. 4). Referring to Fig. 4 one can see that, for a receiver positioned directly over the hitch (i.e., x/b = 0) deviations of the hitch height are detected directly (1:1) by the receiver, but variations or changes in plowing depth are not detected; this receiver position (x = 0) maintains the hitch point such that it travels on a path (line) parallel to the desired drain grade, but this does not provide positive grade control because the plowing depth is not 'directly' related to hitch height. Where the receiver is positioned directly above the plow blade (i.e., x/b = 1), variations in hitch height are not detectable until the plow blade actually varies from its desired depth, thus resulting in significant fluctuations in the plowing depth and the drain channel gradient. Thus, a compromising (or optimum) receiver position is somewhere between the hitch and blade. Based on computer simulation results, Fouss (1971) proposed that $x/b \approx 5/6$ as a "general guideline" for good automatic grade control of a long floating-beam draintube plow. We conducted several field tests with the prototype draintube plow (Figs. 2 and 3) for the cases $x/b \approx 1/2, 2/3, 3/4$, and $5/6$. The results confirmed that values in the range, $3/4 < x/b \lesssim 5/6$, provided the best grade control accuracy.

The accuracy of grade control was checked and recorded in the field by use of a movie camera equipped with a telescopic lens. The camera, mounted on a sturdy tripod, was set up directly behind the plow with the line-of-sight pointing in the direction of travel and also aligned parallel to the projected "laserplane" reference. A reference mark was made or noted on the plow blade which laid on the line-of-sight (i.e., cross-hairs in the telescopic lens). If the plow blade stayed "on grade" as travel across the field progressed, the reference mark on the blade remained aligned with the line-of-sight. In subsequent reviewing of the movie film, a horizontal center-line across the projection screen (not on film) served as a line-of-sight datum.

To summarize the above results, both depth and grade are positively controlled only if the laser receiver is positioned closer to the plow blade than to the forward hitch point of the plow beam. This is particularly true if different soil types are encountered along the path of a drain line. To explain in more detail the type of grade control error which results from the laser receiver being too far forward of the plow blade, the following example is given. Consider a drain being installed where the land is flat (no slope), except possibly for a few minor ground surface irregularities. Thus for a drain to be laid at a grade, the plowing depth must decrease as the tractor moves across the field (assuming direction of ground travel is up-grade). The normal procedure under these conditions is to set the laser transmitter to project one axis of the laserplane parallel to the desired gradient for the drain line. The field studies showed that the resulting drain gradient was steeper than the slope at which the laserplane was projected.†† This type of response in the plowing depth (which is similar to the relationship between hitch height and plowing depth) occurs because the laser receiver is too far forward and a 'direct' relationship does not exist between height to the receiver above the ground surface and plowing depth.

For the desired mounting position, that is $x/b \approx 5/6$, a "mounting arm" can be extended almost directly forward of the plow blade from the tool-bar (i.e., the receiver mast would extend above the tractor cab from the rear), thereby essentially eliminating any depth and grade errors resulting from sideward "tip" of the plow frame when the off-center experimental mounting positions were used (Fig. 3).

FIELD WORK PROCEDURES

One practice of handling the corrugated plastic drainage material in the field is to place the coiled tubing on a spindle mounted on the drainage machine from which it uncoils and feeds directly into the plow's hollow-bladed installation tool. More than one coil of the plastic tubing can be carried on the machine, and as one coil is nearly installed, forward travel is stopped to permit coupling to the next roll so installation can continue. Another practice for field handling is to uncoil the tubing and lay it offset but parallel to the proposed drain line, as shown in Fig. 3. Several types of uncoiling mechanisms have been devised to speed up this operation; one of the more successful ones in use is shown in Fig. 5. With such a mechanized uncoiling device, one man can keep tubing laid out on the ground ahead of the drainage machine.

Our experience with the prototype draintube plow led us to recommend that the tubing be laid out on the ground in advance; this results in a much more efficient field operation of the high-speed plow equipment because it is not necessary to stop for coupling on each new roll of tubing. Considering an average ground speed of 125 fpm with the drainage plow, one roll of tubing (each about 250 ft in length) is installed about every 2 min of ground travel. For installations made during extremely hot weather (e.g., 90 F and up), however, feeding directly from the

**Note: The controller can be factory adjusted to provide *two* durations of correction to obtain minor and major feedback motions; for some kinds of machines this is desirable or even necessary.

††Note: This characteristic response was predicted in computer simulation studies by Fouss (1971).

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DRAINTUBE PLOWS

(continued from page 42)

coil may be desirable to prevent excessive stretch of the plastic tubing; this could keep the tubing cooler since its exposure to sunlight rays prior to installation would be reduced. The tube guides and feeding devices should be designed to reduce frictional drag on the tubing as much as possible. In any event, the percentage stretch of the corrugated tubing installed with a high-speed draintube plow can be less than that occurring with slower moving trenching machines (assuming the same frictional drag factor) because the tubing is under a "stretch load" a shorter period of time during the placement operation. [Reference discussion on stretch versus time by Drablos and Schwab in their paper presented at this Symposium.] To prevent excessive initial deflection of the tubing once it is in the "mole channel", several minutes should be allowed to elapse before the installation slit is closed by compaction (especially on hot days).

A drain line is easily started and connected with the main or collector drain if a back hoe is used to excavate a short (4-5 ft) starting trench. If the starting trench is not provided next to the main, then the plow point can be started into the ground 15-20 ft on the other side of the main and allowed to "float" down to a depth just above the main as the plow approaches the intended intersection; hand excavation can be used if necessary to remove the loosened soil to make the "Tee" connection between the main and lateral.

Future reports will cover such additional items as calibration and operation of laser receiver-controller equipment, operation in rocky soils (which has not presented severe problems), making proper tube couplings, and, the economics of operating the plow-type drainage equipment. Because of the high installation rates, large jobs must be available for the contractor to profitably operate the new equipment.

ADDITIONAL EQUIPMENT DEVELOPMENT NEEDED

The principal features of the draintube plow equipment that needs further design and development work pertain to special applications, such as, installation of larger size tubing (up to 6-in. diameter at least); simultaneous installation of the corrugated tubing with a gravel envelope (as used in the Western U.S.), and using a vibratory leading edge on the plow blade to reduce draft.

With the recent interest expressed by industrial firms and drainage contractors, it seems certain that draintube plows patterned after the design discussed here will soon be commercially available.

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