WEIGHING LYSIMETERS FOR THE DETERMINATION OF CROP WATER REQUIREMENTS AND CROP COEFFICIENTS

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ABSTRACT. *Weighing lysimeters are accurate instruments to measure crop evapotranspiration. Three weighing lysimeters, consisting of undisturbed 1.5- × 2.0-m surface area by 2.5-m depth cores of soil, were constructed and installed at the Texas Agricultural Experiment Station in Uvalde, Texas. Two lysimeters, each weighing approximately 14 Mg, were located beneath a linear irrigation sprinkler system and used in the field production of several crops commonly grown in the area. The third lysimeter was constructed and is used to measure reference ET from a well-watered, grass (ET_{os}) located adjacent to the field lysimeters. Design construction, installation, engineering details and other considerations to ensure acceptable performance of the lysimeters are discussed. The lysimeter facility was developed to accurately assess crop water requirements of vegetables as well as other field crops grown in the Winter Garden region of Texas. Preliminary detection capability of the scale system is also reported.*

Keywords. *Weighing lysimeters, ET measurement, Crop water measurement, Lysimeter construction, Crop coefficients.*

In arid and semi-arid regions, water resources are limited, and competition between urban users, industry, and agriculture is intense. Consequently, all irrigation water use needs to be optimized. Currently, actual crop water requirements for many crops, detailed by crop phenological stage, are not available, and many producers often apply significantly more or less irrigation water than the crop requires. By relating the required water use of a specific crop to a well-watered reference crop such as alfalfa or grass, crop coefficients (K_c's) can be determined to assist in predicting accurate crop irrigation needs using relatively simple meteorological data. Reference evapotranspiration (ET_o), computed from weather data measured at an agricultural weather network station together with crop coefficients for specific crops, is a widely accepted procedure to estimate crop water use using the following equation:

$$ET_c = (K_c ET_o) \tag{1}$$

where

ET_c = crop evapotranspiration,

K_c = crop coefficient, and

ET_o = reference evapotranspiration.

Lysimeters have been used for decades to measure water use for a variety of crops. Many previous designs have involved the use of differing sizes and types of scale systems to address specific objectives and to keep costs and accuracy within acceptable limits (Harrold and Dreibelbis, 1958; Pruitt and Angus, 1960; Van Bavel and Myers, 1962; Libby and Nixon, 1963; Ritchie and Burnett, 1968; Rosenburg and Brown, 1970; Armijo et al., 1972; Powers et al., 1971; Ehling and LeMert, 1976; Reicosky et al., 1983; Aase and Siddoway, 1982; Wright, 1982; Brun et al., 1985; Devitt et al., 1983; McFarland, 1983; Dugas et al., 1985; Howell et al., 1985; Marek et al., 1986; Bergstrom, 1990; Allen and Fisher, 1990; Young at al., 1996; Yang et al., 2000). Further reviews of design and discussion of lysimeters for water use measurement can be found in Kohnke et al. (1940), Tanner (1967), Rosenburg et al. (1968), Abouklaled et al. (1982), Kirkham et al. (1984), Soileau and Hauck (1987), Hatfield (1990), Jensen et al. (1990), and Allen et al. (1991). With the advent of modern computers and dataloggers, continuous monitoring of weighing lysimeters is readily possible. The most representative units typically have monolithic cores where soil structure and associated parameters remain unchanged, as disturbed soil cores may affect plant growth conditions significantly. In recent times, research agricultural engineers developed a method to acquire moderate to large-sized monolithic cores with the use of hydraulic jacks to reduce costs associated with the acquisition process (Schneider et al., 1988). This method was used in acquiring the large, weighing, monolithic lysimeters located at the USDA-ARS facility at Bushland, Texas. Pull down force requirements in the silty clay soil profile was on the order of 712 KN for the monolithic cores of the 10-m^2 surface area and 2.4-m depth. The process has proven that lysimeter cores can be taken in a day or less with an excellent degree of plumb acquisition control and provide a high degree of safety to personnel as

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compared to other acquisition methods. Subsequently, the hydraulic acquisition technique has been successfully used by the authors several times to acquire monolithic lysimeter cores for a range of soil types.

Other engineering aspects of lysimeter design entail consideration of ample surface area to represent and accommodate cultural row spacing(s) and minimization of perimeter (edging) and gap area as compared with the actual lysimeter soil surface area. Drainage partitioning within the bottom section, seepage restriction in the upper region, water table control capability, drainage porting, and excavation capabilities also deserve careful consideration and require suitable planning to facilitate acceptable operation and performance of the lysimeter. Excavation, traffic control and compaction issues during acquisition must also be adequately considered and controlled. Access to the lysimeter for maintenance and repair should also be considered to minimize the impact of using crane equipment in the future in case of scale malfunctions. Lastly, electronic data acquisition equipment should be reviewed and chosen appropriately to ensure data acquisition capabilities and measurement accuracy. The objective of this construction and installation effort is to discuss several of the engineering details and processes required for an acceptable monolithic lysimeter for use in the determination of crop water use and crop coefficients.

Construction and Fabrication Methodology

The location of this lysimeter effort was at the Texas A&M Agricultural Research and Extension Center at Uvalde, Texas (Latitude: 29° 13’ 03”, Longitude: 99° 45’ 26”, Elevation: 283 m). The size of the monoliths selected for the facility was 1.52 × 2.03 × 2.13 m deep to accommodate the two common cropping row spacings used within the Uvalde “Winter Garden” region. The soil monolith boxes were constructed of 9.5-mm thickness mild steel plate and fabricated with a desired, sidewall straightness tolerance of ±1.6 mm.

The core profiles were acquired adjacent to the lysimeter field. Soil sampling verified that the acquisition site soil profile was characteristically similar to that of the lysimeter site soil profile in the experimental field. Acquisition was obtained at the adjacent site rather than at the lysimeter field site so as to minimize disturbance and compaction from heavy equipment traffic during the acquisition phase of the process. Also, the soil perimeter area around the outside tank did not have to be excavated to the degree (width) as would be required if acquisition had taken place in the field site(s) in accordance with agency safety regulations. As conducted, perimeter excavation of only approximately 8 to 10 cm outside the outer tank dimensions at the field sites was necessary to clear the exterior reinforcing members of the outside tank. The monolith tanks were reinforced in the upper portion of the lysimeter tank by a heavy, inner flat bar member that also serves to divert irrigation water flow along the interior wall toward the interior of the monolith if any soil to wall separation occurs. (This interior bar has been referred to as an anti-seep collar in prior designs.)

The outside tank was constructed in two sections consisting of an upper or “top hat” portion and a larger, lower portion referred to as the outer tank or base tank section. The top hat section was designed to more precisely set the gap along the perimeter of the lysimeter tank after all the other construction aspects were completed. Note in figure 1 that no outside reinforcing members are located in the upper portion of the lysimeter tank, which corresponds to the depth to which the top hat is set. The top hat interior dimensions are less than those of the lower tank to keep the air gap to lysimeter surface area ratio at an acceptable value. The targeted, above ground top lip air gap between the monolithic tank and outer box was designed to be 9.5 mm.

Reinforcing members were equally spaced along the outside walls (sides) with specialized welding processes that minimized distortion due to welding stresses. The welding sequence utilized during fabrication was an alternating process along all four sides in a sequential, side-alternating manner to allow maximum time for cooling per intermittent weld before any adjacent welding was conducted. This fabrication sequence reduced sidewall warpage and distortion while allowing the welding personnel to “virtually” continuously weld on some portion of the unit, minimizing overall fabrication time and costs. Internal and external reinforcing with 9.5- × 51-mm flat bars were engineered into the design to resist compression “bulges” during the acquisition and lifting phases. The 9.5- × 51-mm flat bars were also designed to resist clay-swelling forces during wetting cycles of the soil profile. Setting and sealing of the outer top hat portion to the base section was achieved using a band of 100% silicone compound sealer and ASTM Grade 5 bolts spaced closely to allow separation and release of the top hat in case access is required for scale repairs.

The hydraulic pull down assembly (fig. 1) and technique of Schneider et al. (1988) was used with relative ease for acquisition of three monolithic lysimeter cores. The method uses sacrificial, concreted, bell-bottomed anchors in a rectangular (corner) configuration to accommodate the jacking base assemblies shown around and atop the lysimeter tank (fig. 1). The illustrated configuration utilizes a heavy, temporarily attached (intermittently welded) reinforcing angle iron member near the lower edge of each side of the lysimeter tank with intermediate, external, cutting lip support pipes (columns) to assist in uniformly transferring the downward forces imposed along the large W beams by the base of the hydraulic jacks. Also, the transfer of force is aided by the reinforcing gussets between the W beam’s lower flange and web at the columnar compression points. This

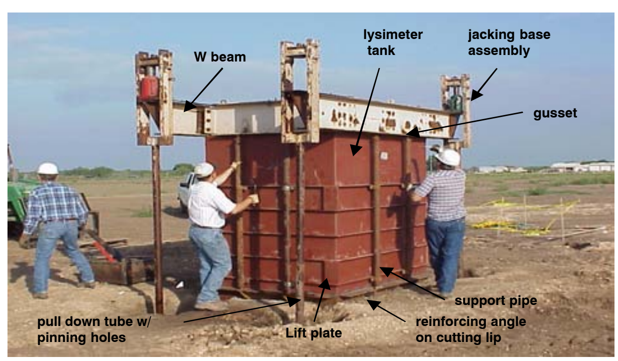

Figure 1. Hydraulic pulldown assembly used to acquire the monolithic lysimeter cores at the Texas A&M Agricultural Experiment Station, Uvalde, Tex.

configuration effectively protects the cutting lip from distortion during core acquisition. (The beveled cutting lip actually shears the soil to the outside of the lysimeter tank during the acquisition process.) Perimeter soil excavation around the monolith in similar increments to the pinning increment of the pull down tubes precedes the pull down process to allow the monolith cutting edge to advance. In this case, a soil excavation increment of 0.3 m was used with a pinning increment of 0.15 m. This incremental excavation, with stepwise pinning, is essential for a proper shearing edge process to occur, thereby maintaining a straight, as opposed to a bowed, bottom cutting edge. Once the hydraulic jacking assemblies are lowered to the desired core acquisition level below the top edge of the lysimeter tank (in this case, 10 cm), the pull down process is complete. Subsequent placement of a temporary top on the unit and insertion of large, flanged, beams in a hooked shape beneath the monolith to retain the soil intact at the bottom during the lifting and over−turning processes completes the acquisition phase.

During these and all associated construction operations, caution must be exercised and safety measures must be strictly enforced as the large and heavy caliber of equipment utilized in these processes can result in serious injury in the event of accidents. Thus, hard hats and protective hand wear should be required worn by all participants near the activity site(s). Additionally, a single site supervisor should be determined and be in charge of related operations at all times.

Once acquisition (pressing into the ground) of the monolith(s) was completed, a large crane was utilized to lift the monolith(s) out of the ground and overturn each core sequentially to an inverted position to allow for preparation and placement of the drainage system. The crane for this operation must be able to accommodate the mass of the monolith plus handle the moment created by the crane being located as far from the lysimeter placement site as possible to reduce soil compaction. The use of a spreader bar is highly recommended in the lifting and turning operations to prevent horizontal compressive forces from being exerted on the monolith sidewalls by the lifting cables. Each monolith was turned using W beams vertically attached to the lift plates (see fig. 1) on the sides of the monolithic tank with high strength, ASTM grade A325-N, 19-mm diameter bolts torqued to proper specification.

Once the monoliths were overturned, approximately 100 mm of parent material was excavated from the bottom of the monolith. Each monolith was then outfitted with a partitioned, multi-sintered tube, stainless steel drainage system (fig. 2) to allow for extraction of percolated water and related soluble compounds once in operation. Once routing of the tubes was concluded, the drainage system was then packed in a uniform, ultra-fine sand media. The depth of the routing lines was required to be higher than the 100-mm internal drainage partitions attached to the bottom plate. Subsequently, multiple pass welding around the perimeter sealed the bottom plate (9.5 mm in thickness) of each of the soil monolith boxes. In figure 2, the four interior tubes were partitioned and routed in an adjacent manner with the perimeter tubes being routed individually to a mid-way, central location at one of the sidewalls. Each tube is plumbed separately as a preventative measure in case of plugging or other malfunction of a tube.

Figure 2. Multiple partitioned sintered tube drainage system placed in each Uvalde monolithic lysimeter.

The next process involved excavation of the field sites to accommodate the foundation and placement of the outer tank. To expedite excavation, a large 1.53-m diameter boring auger was utilized to excavate the majority of the outer tank soil at the field sites. This diameter corresponded to the minor axis of the lysimeter dimensions. A barrel assembly was subsequently lowered into the excavated hole and utilized for corner soil accumulation. The corners were sloughed off into the barrel with only the bottom area having to be manually shoveled out. With the depth of the excavation of nearly 2.8 m, temporary sidewall reinforcing was needed for safety. This was provided through the use of 3.8-cm diameter electro-mechanical (EMT) tubing 3 m in length spaced closely along the respective wall sections and attached to a rectangular wooden frame on the soil surface. In this manner, the tubes were held ("staked") 0.3 m below the excavated depth providing safety for personnel from sidewall cave-in or sloughing.

Foundations for the lysimeters were established at a depth of nearly 2.74 m below ground level. Each foundation was engineered to provide an ultra-stable base for the platform scale. The minimum nominal thickness of the foundation was 15.3 cm with scale supporting areas receiving a minimum of 31 cm of 27.6-MPa concrete. All reinforcing in the foundation was arranged in a minimum grid of 25 cm with stress points receiving a 15- to 20-cm grid spacing. All reinforcing in the concrete was completed with 1.91-cm diameter concrete reinforcing bars. Foundation drainage, including slope to the center of the foundation and a gravel base, was incorporated into the design to allow water to drain beneath the foundation in the event of leaks or surface overflows. The depth of the drain was approximately 1 m below the foundation elevation.

To ensure accurate placement and positioning of the scale support plates at the desired elevation, steel plates were fabricated (tack welded) onto a temporary frame (fig. 3). Platform feet rested upon this temporary frame during the foundation concrete pour. The plates were suspended at the correct elevation allowing concrete to be poured, vibrated, worked and formed without attempting to level the feet while other operations were being conducted. As space in the excavated hole was essentially limited to one person for the shaping and finishing operations, this turned out to be a significant step in setting the correct elevations. Another

Figure 3. Platform scale support plates held in place for concrete pouring with temporary bar members. "L" shaped reinforcement rod members are welded beneath the plates for scale stability.

useful tactic used to shape the concrete to the center drain during the pour was placement of a stubbed section of pipe into the gravel drain with a circular plate atop the 0.5-m length stub and have a workman lay on it and swivel 360 degrees (as on a pedestal/turntable) to screed, slope, and finish all areas of the concrete floor toward the center drain. After the concrete had set, the one-sided tack welds used to hold the scale plates in place during the concrete pour were torqued over and broken off, and the small, residual weld(s) were ground off leaving the scale plates correctly oriented and level, and ready for final painting. After setting the lower portion of the outside tank, sealing it to the rectangular frame with the concrete pour, and painting the assembly with marine grade epoxy paint, the finished result of the outer tank assembly was complete (fig. 4).

The scale systems used in the design consisted of platform-type scales capable of weighing the entire soil mass, yet sensitive enough to detect small crop water changes. These scales utilize four weight beam mechanisms at the corners, which are essentially horizontal load cells with ultra sensitive strain gauges suspended to the platform by the use of three heavy chain links. Thus the platform top is allowed to move or sway to a resting point of equilibrium. In effectively using only one movable link (the center one of the three, as the outer links are fixed), the scale exhibits minimal oscillation, of the platform in light winds with a crop. The scale further utilizes an electronic accumulator to concatenate the four load cell measurements into a central analog output. Each platform scale has a total capacity of 18 Mg.

Following relocation and placement of the lysimeter cores at the lysimeter field site, the top hat assembly was installed. Temporary spacers were inserted in each corner of the top hat to properly gap the sides while the assembly was sealed and

Figure 4. Completed lower, outer tank assembly at the field site with sloped, center drain and the four scale supporting plates.

bolted to the lower base tank. Caution has to be exercised in this operation to set the top hat section to the equilibrium point of the lysimeter on the scale with the spacers and not move the lysimeter off the equilibrium point. Otherwise interference will occur when the spacers are removed. Temporary taping of the gap was used to keep soil from entering the gap space and possibly creating drag or other interference between the two walls until the final gap sealing film was installed. The target gap of 9.5 mm was attained. Once the attachment procedure was complete, the tape was replaced with a flexible Mylar membrane in a "looped" manner that was used to seal the interface gap.

Scale Calibrations and Discussion

Since the scale-type selected for this installation is fully assembled as a unit, as compared with counter-balance beam-type scales, a pre-calibration was conducted to ascertain proper operation. Initial calibrations indicated that two of the scale units damaged in shipment required additional repairs to bring the units up to original design performance specifications. Preliminary scale calibrations conducted indoors with limited mass containers (conducted below the proposed loading range) indicated acceptable performance with a detectable limit on the order of 125 g. After placement in the field, very good repeatability with coefficients of determination exceeding 0.9999 (fig. 5) was attained.

Calibration of the lysimeters in the field followed procedures described by Howell et al. (1995). Each lysimeter was covered with a plastic sheet to slow evaporation during the time of the calibration sequences. Four large weights equivalent to 100 mm of water on the lysimeter was the basis for each subset of data. Each subset was a series of loading the scale with ten 22.8-Kg weights followed by a series of 1.0-, 0.5-, 0.2-, and 0.1-Kg laboratory weights for sensitivity analysis. Unloading was conducted in a reverse sequence. The loading and unloading sequences provided a hysterisis assessment of the scale and data logger combination, as weight was increased or decreased by like amounts. The data logger(s) were programmed to read the scales once every second and to integrate the data for 1-min outputs. The

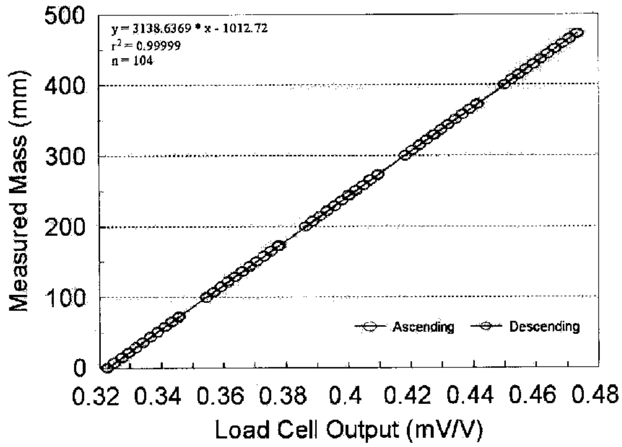

Figure 5. Plot of a platform scale calibration showing very good correlation with little or no hysteresis.

weights were allowed 1 to 2 min of settling time followed by 2 to 3 min of output data to the data logger. Calibrations were performed on days when wind conditions were relatively light to prevent "sway" noise on the scales.

Detectable resolution values of approximately 113 g on the 18-Mg scales were measured with a precision Campbell Scientific CR23X electronic data logger. This represents a detectable depth resolution of 0.0036 mm over the soil surface. The datalogger unit was configured to utilize an input scale range of ±10 millivolts and had a resolution differential of 0.33 microvolts for detecting changes in mass.

After several months of operation, one of the two field scales, which was originally damaged, began to exhibit drift in the data that was not attributable to crop water loss. The lysimeter had to be pulled out of the ground (with the use of a 68-Mg crane), and the electronics were completely replaced. Cost to the project was substantial. Thus, a lysimeter design of this "closed" type without direct access to the scale system has potential project consequence in terms of costs and data loss when scale systems malfunction. This risk should be an important design consideration in planning a weighing lysimeter facility.

Figure 6. Completed field lysimeter awaiting next crop at the Texas A&M Research and Extension Center at Uvalde, Tex. Note basic meteorological instrumentation at the site during this period.

Figure 7. Completed grass reference lysimeter located near the field lysimeters at Uvalde, Tex.

Figure 6 illustrates the completed installation of one of the field lysimeters showing the bedding (and furrowing) field operations in preparation for the next planting following an onion crop. Finishing of the beds and furrows has to be accomplished by backing up farm equipment near the lysimeter, and ultimately completed with hand tools adjacent to and within the lysimeter boundary. Figure 7 illustrates the completed grass lysimeter facility. The ET_{os} (Allen et al., 2005) site, which uses a well-watered grass reference, utilizes an accurate and representative set of meteorological instruments to correlate measurements to numerous parameters with the lysimeter measurements.

Summary

The acquisition and construction of monolithic lysimeters involves complex processes and details and requires a significant degree of planning and oversight to ensure that targeted goals are attained. In addition, a sound practical working knowledge of construction equipment and processes are essential to ensure the safety of personnel associated with an installation of this magnitude. At the time of completion, no injuries had been experienced with the effort.

The installation of these lysimeters was relatively rapid and "easy" due to the experienced engineering personnel associated with and overseeing the project. Total time required for the project from fabrication initiation to field completion was approximately 9 months for all three lysimeters. This accomplishment alone is substantial testimony to the dedication and commitment of the individuals involved in the project.

The targeted objectives with respect to the construction and fabrication aspects of this lysimeter project appear to have been met. Despite the difficulty incurred with the damaged scale systems, it is envisioned that the design used for this facility will provide scientific water use data for years to come and will benefit the producers of the Winter Garden region of Texas.

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